Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations | 1. Thesis and Dissertation Collection, all items

1970-05

Distortion removal in structural weldments

Duffy, David Kenneth

Cambridge, Massachusetts; Massachusetts Institute of Technology

http://hdl.handle.net/10945/14959

Downloaded from NPS Archive: Calhoun

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

DISTORTION REMOVAL IN STRUCTURAL WELDMENTS

David Kenneth Duffy

DISTORTION REMOVAL IN STRUCTURAL WELDMENTS

by

DAVID KENNETH DUFFY

B.S., United States Coast Guard Academy

(1965)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREES OF

MASTER OF SCIENCE IN

NAVAL ARCHITECTURE AND

MASTER OF SCIENCE IN

MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1970

LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIF. 93940

DISTORTION REMOVAL IN STRUCTURAL WELDMENTS

by

DAVID KENNETH DUFFY

Submitted to the Department of Naval Architecture and Marine Engineering on May 21, 1970, in partial fulfillment of the requirements for the degrees of Master of Science in Naval Architecture and Master of Science in Mechanical Engineering.

ABSTRACT

The use of flame straightening of welded structures is discussed along with other methods including those which are just being developed. System models were constructed of 3/8 inch AISI 1020, low-alloy, high-strength U. S. Steel Corten, and quenched and tempered U. S. Steel T-1 plates. These models were designed to resemble panel structures encountered in shipbuilding. Welding procedures for all samples were held constant. Point of application of the flame as well as quenching techniques, were varied in the experiments.

The results of testing are presented in the form of distortion plots of the samples. Plots were made as welding proceeded and as various flame straightening methods were tried. In this study, it was shown that for the same welding procedure, the amount of distortion decreased as the yield strength of the materials used was increased. Flame heating with a water quench afterwards was the only technique found to be effective on this type panel structure. It was shown that there is probably no corridor of yield strength where flame straightening is most appropriate, rather factors such as boundary conditions and heating techniques appear to be the more controlling variables.

Recommendations for additional study are given with emphasis on developing an analytical model and testing various techniques of flame and quench application in order to determine optimum methods.

Thesis Supervisor: Prof. Koichi Masubuchi

Title: Associate Professor of Naval Architecture

ACKNOWLEDGEMENTS

I would like to thank the U. S. Coast Guard for sponsoring my studies at M.I.T. and this thesis.

I also thank Prof. Koichi Masubuchi, my thesis advisor, for his assistance and frequent helpful suggestions.

In addition, I want to thank Mr. Clayton O'Hara and Mr. Arthur Mosman of Ramsay Welding Research, Inc. for their very kind assistance throughout the experimental work.

Finally, I thank my wife, Donna, for her efficient typing of this thesis.

TABLE OF CONTENTS

	Page
Title Page	1
Abstract	2
Acknowledgements	3
Table of Contents	4
List of Figures	5
List of Tables	7
I. Introduction	
A. Background	8
B. Previous Investigation	16
II. Procedures	
A. Selection of Parameters	24
B. Experimental Procedure	26
III. Results	37
IV. Discussion of Results	46
V. Conclusions	55
VI. Recommendations	56
VII. Appendix	
A. New Techniques	60
B. Summary of Data	66
VIII. References	99

LIST OF FIGURES

Fig.		Page
1	Behavior of ASTM A-36 Steel as a function of temperature	11
2	Cross section of 1/4 inch plate spot heated to 1700° F.	13
3	Cross section of 1/4 inch plate spot heated to 1550° F.	14
4	Cross section of 1/4 inch plate spot heated to 1100° F.	15
5	Spot heating technique	17
6	Linear heating technique	17
7	Linear heating of fillet weld backs	18
8	Specimen from previous investigation	20
9	Specimen from previous investigation	20
10	Specimen from previous investigation	21
11	Specimen from previous investigation	21
12	Relative seriousness of distortion problems in relation to plate thickness	25
13	Geometric configuration of system model	27
14	Weld sequence	29
15	Photograph of model on surface plate	31
16	Diagram of grid used for measurements	33
17	AISI 1020 Mid-span deflection after welding	39
18	CORTEN mid-span deflection after welding	40
19	T-1 mid-span deflection after welding	41

Fig.		Page
20	Normalized maximum deflection vs. yield strengths	42
21	AISI 1020 mid-span deflection after flame heating	43
22	CORTEN mid-span deflection after flame heating	44
23	T-1 mid-span deflection after flame heating	45
24	Comparison of results	47
25	Behavior of mild steel at high temperatures	48
26	Behavior of high strength low alloy steel at high temperatures	48
27	Behavior of T-1 steel at high temperatures	49
28	Free Body diagram of weld zone	50
29	Free body diagram of panel	53
30	Weld metal deposited vs. angular deflection of free fillet welds	58

LIST OF TABLES

		Page
1.	Analysis of Materials used	26
2.	Electrode Characteristics	28
3.	Heating Times	36
4.	Weld Metal Deposited	38

I INTRODUCTION

A. Background of Problem

Shrinkage of weld metal and the accompanying residual stresses and distortion is a problem for any industry engaged in the fabrication of structural weldments. The problem is particularly relevant to the shipbuilding industry (1,2,3). Welding is used extensively in shipyards because of its advantages over any other contemporary assembly method.

Many ideas have been advanced as solutions to the problem of distortion. Unfortunately, these ideas and theories are often in conflict. Even though welding has been used extensively in ship construction since the 1930's, there is very little published experimental or theoretical work on the control and removal of distortion.

Residual stresses and resulting distortion in structural weldments are caused by three fundamental dimensional changes:

1. Shrinkage perpendicular to the weld line.
2. Shrinkage parallel to the weld line.
3. Rotation around the weld line.

Due to the fact that these three dimensional changes are always combined, the analysis of distortion is extremely complex.

Longitudinal and transverse shrinkage have to be essentially designed out of a structure such as a ship. If it were not

designed out by making the proper shrinkage allowances, the structure would not fit together when time for final assembly came. Angular changes, particularly in the area of fillet welds, are, however, another problem. Angular changes appear to be more difficult to design out and have to be corrected by some type of post welding operation.

Angular distortion has been removed in the past by the following methods:

1. Mechanical pressing of members which are small enough to be handled by a press.

2. Jacking of members in place. Usually this method requires the welding of a strongback in place to transmit the jacking force. Jacking can be accomplished with or without the application of heat.

3. Hammering of locally heated areas.

4. Peening of the weld metal itself.

5. Cutting the distorted panel, thus removing some material and welding the cut back together.

6. Applying weld beads to the concave side of the panel to cause shrinkage stresses and draw the panel straight.

7. Flame straightening of members in place with the use of the oxyacetylene flame alone or combined with a water quench.

It should be noted that methods 5 and 6 have the disadvantage that resultant weld metal must usually be ground off and are thus less efficient than other methods.

The shipbuilding industry makes extensive use of method 7 and is the basic subject of this thesis.

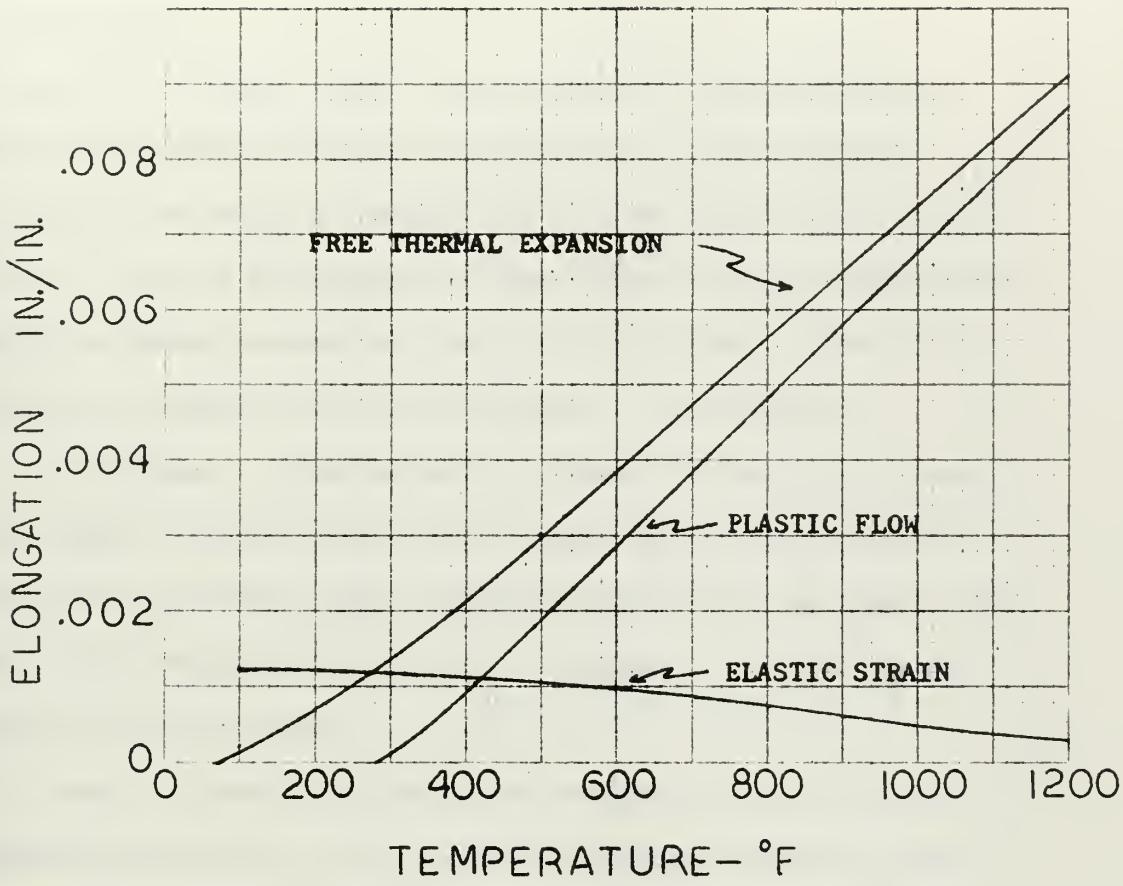
During the first phase of work, an investigation into new metal working techniques which could be used for distortion removal in weldments was conducted. The results of this investigation are included in appendix A.

Generally speaking, the same physical phenomena are involved in flame straightening as those which cause shrinkage and residual stresses in welding. Flame straightening is essentially the application of heat to a localized area of metal to cause dimensional changes. Hopefully, the dimensional changes can be obtained without the use of external forces such as mauls and jacks. Since a highly localized, quickly applied, heat is required, the oxyacetylene flame is used universally in this process. Further impetus for the use of the oxyacetylene flame is provided by the fact that it is an extremely portable and flexible piece of equipment which is used extensively in shipyards for all types of metal fabrication.

Richard Holt (4), who is considered a prime authority on the subject of flame straightening in this country, has stated that three basic factors effect flame bending techniques. These three basic factors are:

1. The thermal expansion of the material with rise in temperature.

2. The variation of the yield strength of the material with a rise in temperature.



Behavior of ASTM A-36 steel perfectly confined on one axis as a function of temperature.

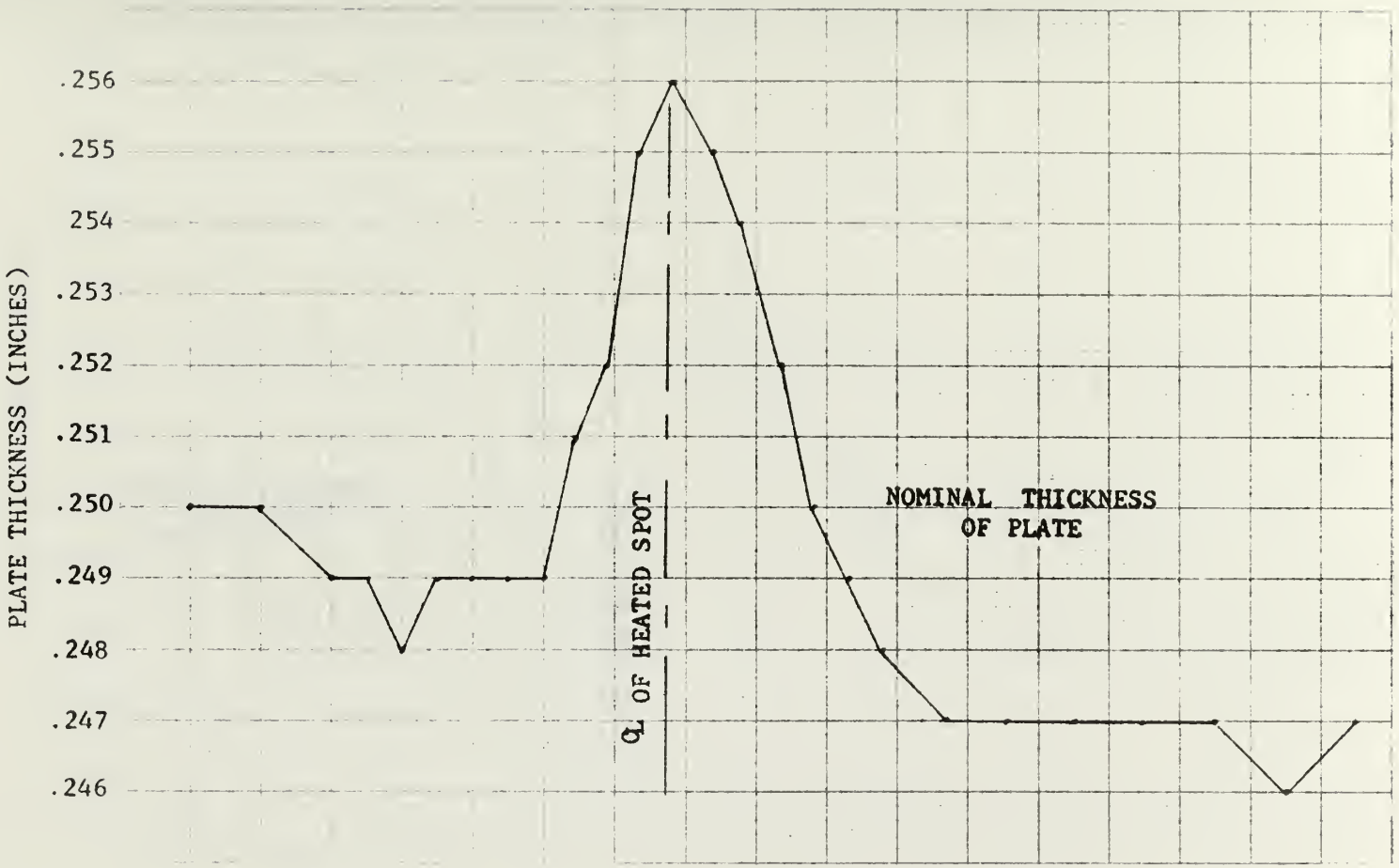
FIG. 1

3. The behavior of the modulus of elasticity at elevated temperatures.

These three factors control the dimensional changes which are required in order that flame straightening be accomplished. As a material is heated it expands unless some constraint is placed on it. If it is constrained in some manner, it will expand until the free thermal expansion is equal to the elastic strain, at which time plastic flow will take place. See figure 1.

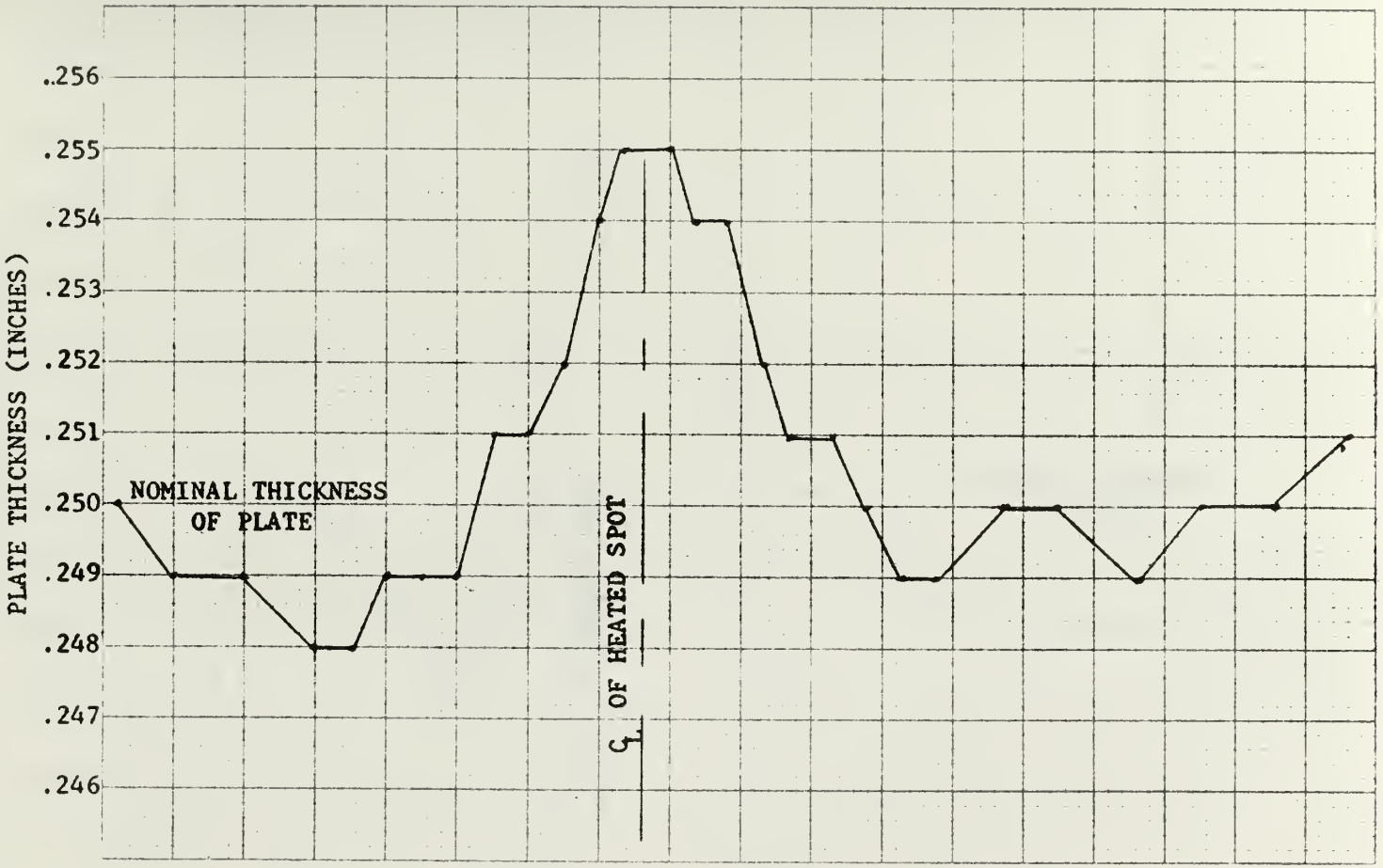
As a plate or other structural member is heated by oxyacetylene flame, the heated area will expand; this expansion will be resisted by the cold rigid surrounding metal with the result that the softer heated metal will flow and upset in a direction perpendicular to the plate.

Leon C. Bibber (5) gives three examples of plates heated to temperatures above, in, and below the critical range of 1330° F. to 1600° F. In any of the cases, when the entire heated area begins to cool, the piece of plate in the heated area has the same weight that it had before, but it has a different shape. If the dimensions of the spot are such that elastic strain will satisfy the tension demands of the shrinking spot, elastic strain only need result. On the other hand, if the demands are too great for the elastic strain, some plastic flow will take place, but elastic strain will also remain, and the volume surrounding the thickened spot will be decreased in the only direction possible, namely, thickness.



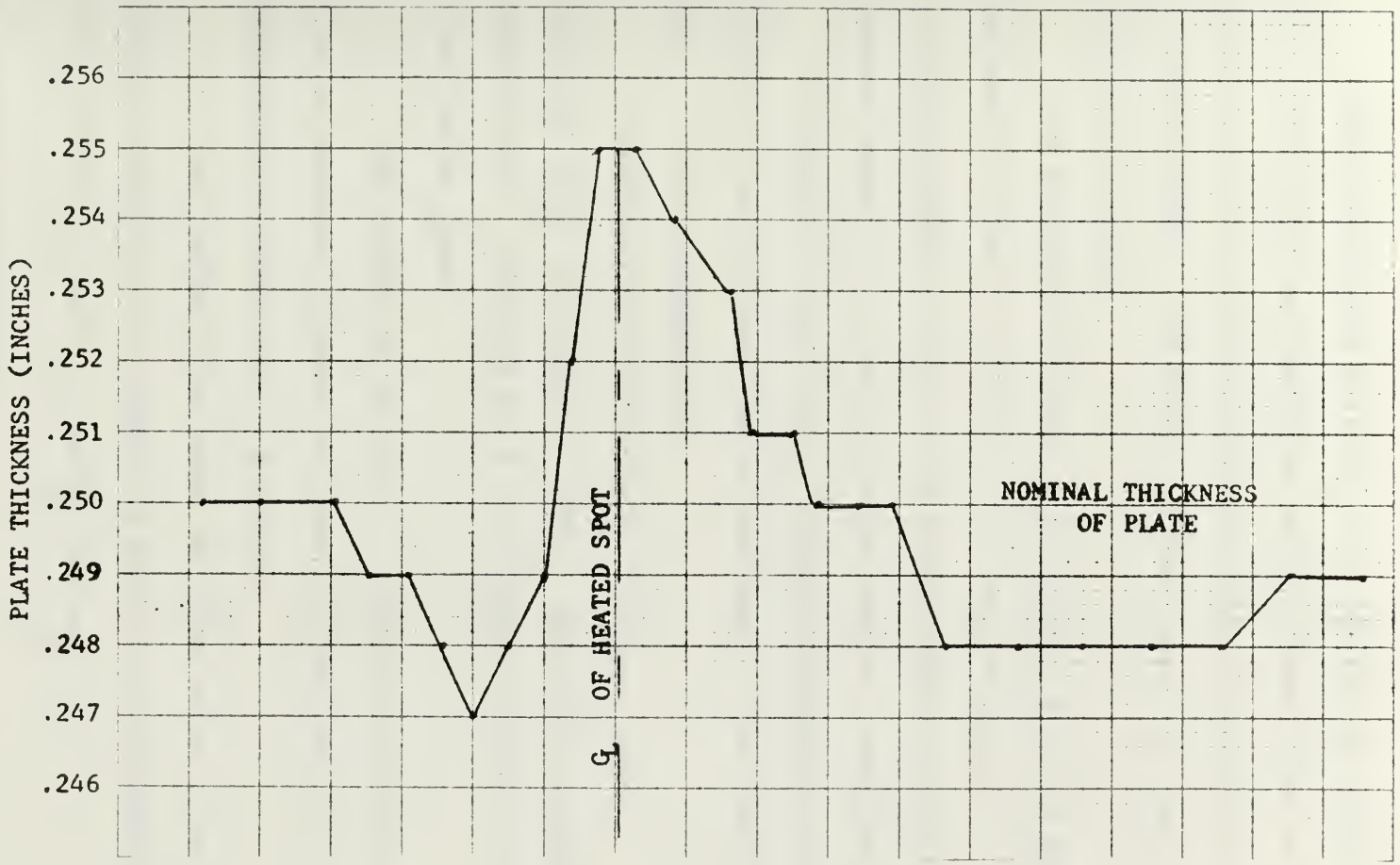
Actual thickening of plate as a result of spot heating to 1700° F.

FIG. 2



Actual thickening of plate as a result of spot heating to 1550° F.

FIG. 3



Actual thickening of plate as a result of spot heating to 1100° F.

FIG. 4

Bibber made actual tests on 1 ft. square, 1/4 inch thick plates which were spot heated to various temperatures and then allowed to cool to show the thickening and thinning effects previously described. The results of these tests are shown in figures 2, 3, and 4.

It is apparent from these three disgrams that the degree of thickening is about the same for all three temperatures, and thus it would be better to work at the lower temperatures just as an economic measure, i.e. savings in gas used and labor involved.

In practice, three types of heating techniques are used to obtain the required upsetting and shrinkage of the distorted plate. These techniques are:

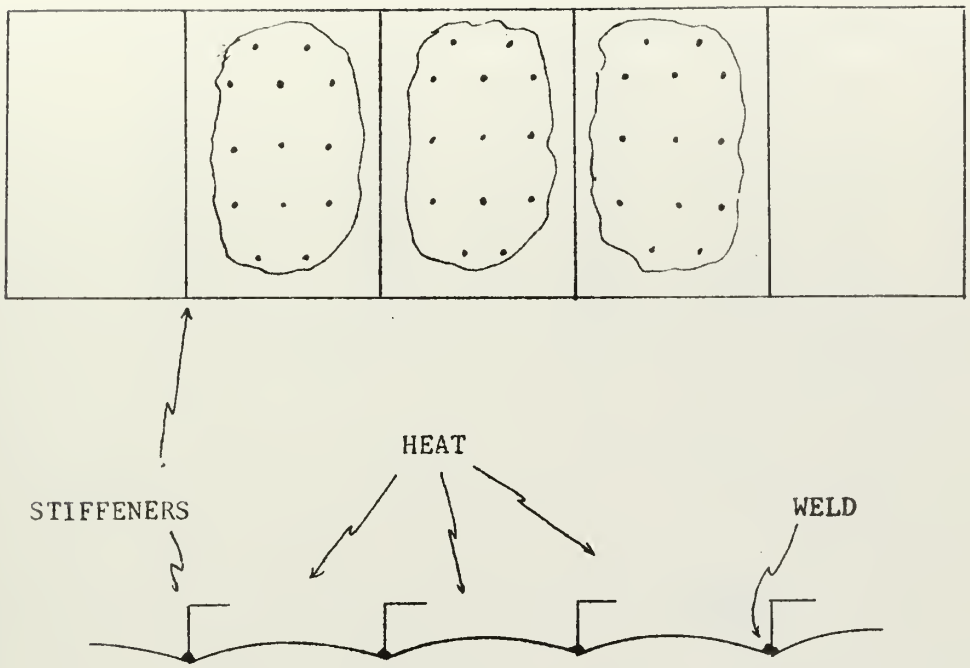
1. Spot heating of the panels. In this procedure individual spots are heated to 1200° F. and rapidly quenched with a water spray. The spots are 1 to 2 inches in diameter and spaced 3 to 8 inches apart.

2. Line heating of the panels. In this procedure the area to be straightened is heated to 1200° F. along narrow lines and afterwards the heated line is quenched.

3. Line heating of the backs of fillet welds. This is a procedure similar to (2) except the flame is applied behind the weld and then the quench is applied to this area.

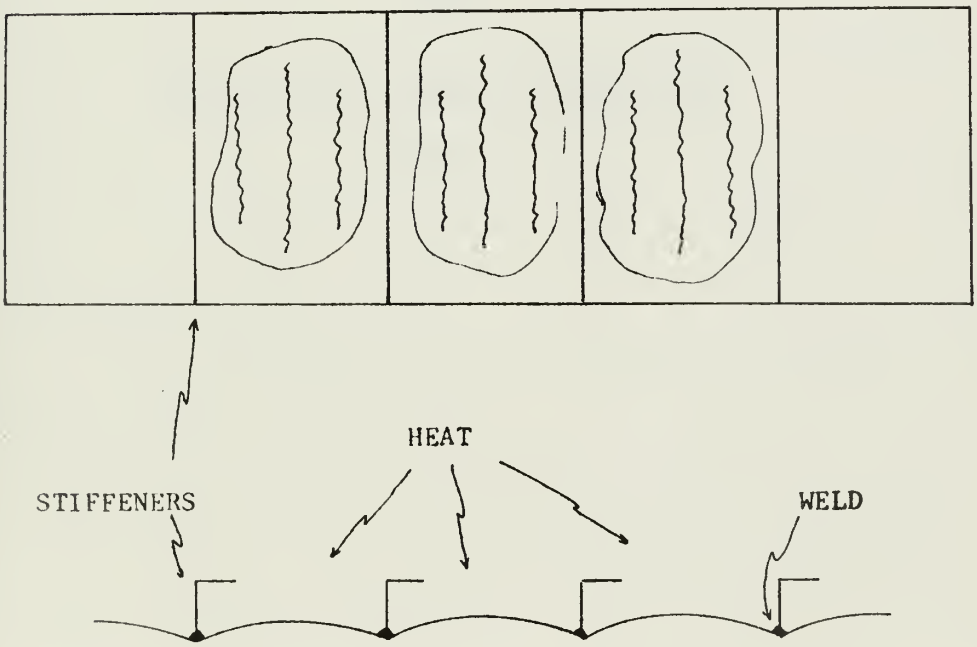
B. Previous Investigations

Although, as has been stated before, flame straightening is a common procedure in shipyards; but there are very few published results of any previous experimental or analytical investigations.



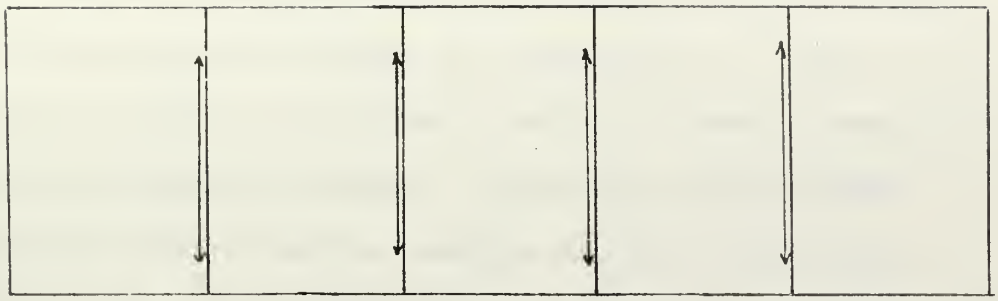
SPOT HEATING TECHNIQUE

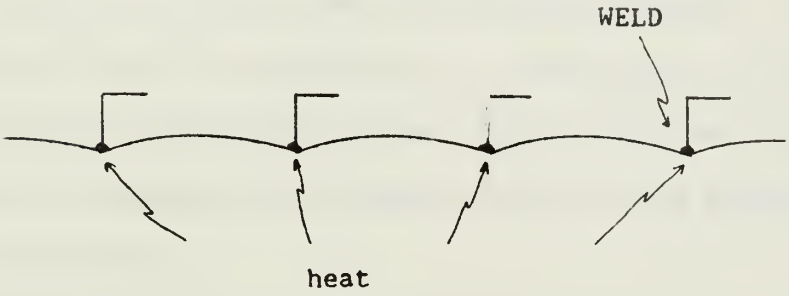
FIG. 5



LINEAR HEATING TECHNIQUE

FIG. 6





LINE HEATING OF BACK OF FILLET WELDS

FIG. 7

Most previous investigations have been concerned with the causes of distortion and the methods for controlling it. This is as it should be; however, the problem of what to do about distortion that cannot be designed out remains. The problem can be brought further into focus when one considers that the welder and/or welding engineer are sometimes the last people to be consulted about a particular design. They are then expected to correct mistakes that have been made before and come up with a finished product.

Two of the most recent investigations in this field have been concerned directly with the flame straightening problem. The first was done at M.I.T. in 1969, by R. A. Walsh (6). His thesis work consisted of constructing system models of mild steel and HY-80 steel and observing the response of each to the procedures of flame straightening.

Walsh constructed four types of system models of 1/2 inch thick plate as shown in figures 8, 9, 10, and 11.

His straightening procedures consisted of spot heating in the range of 1100-1200° F. and applying a water quench.

His conclusions were that:

1. Flame straightening was 2 to 3 times more effective on mild steel than on HY-80 steel.

2. Varying the position of flame straightening techniques from plate mid-span to fillet weld area produces no significant differences in reducing distortion.

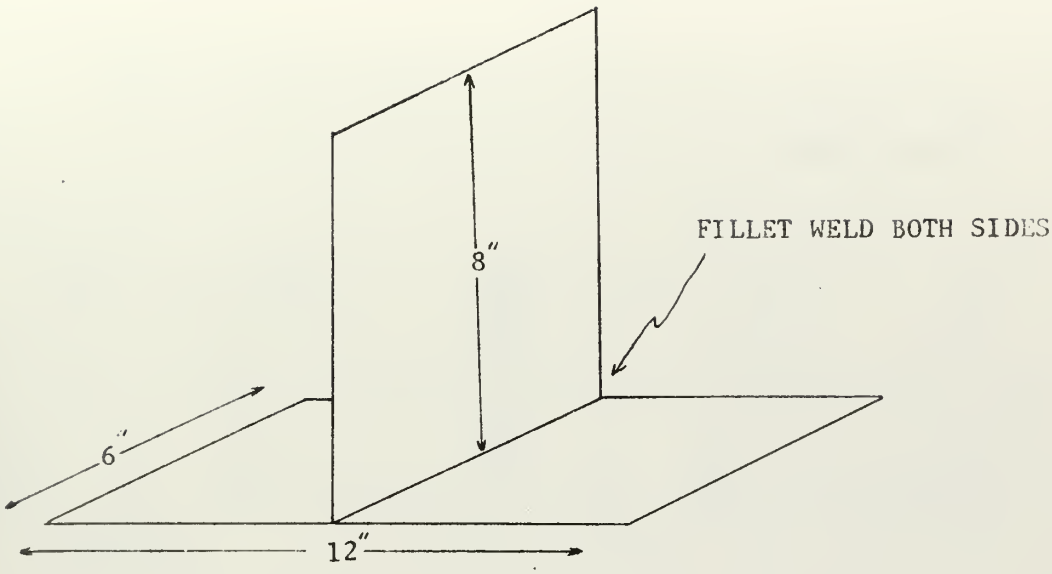


FIG. 8

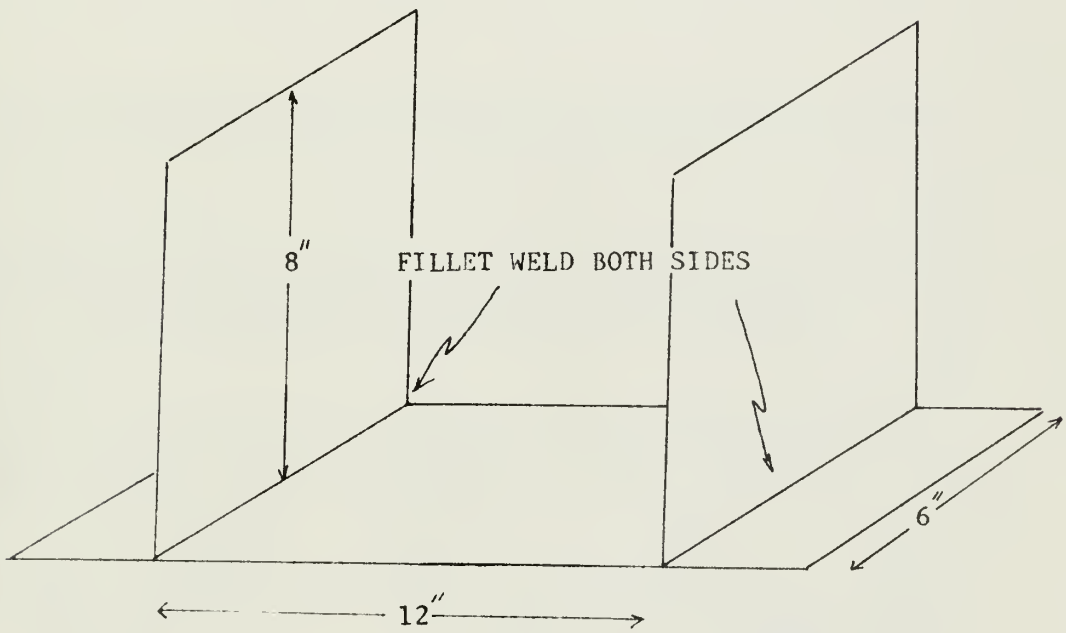


FIG. 9

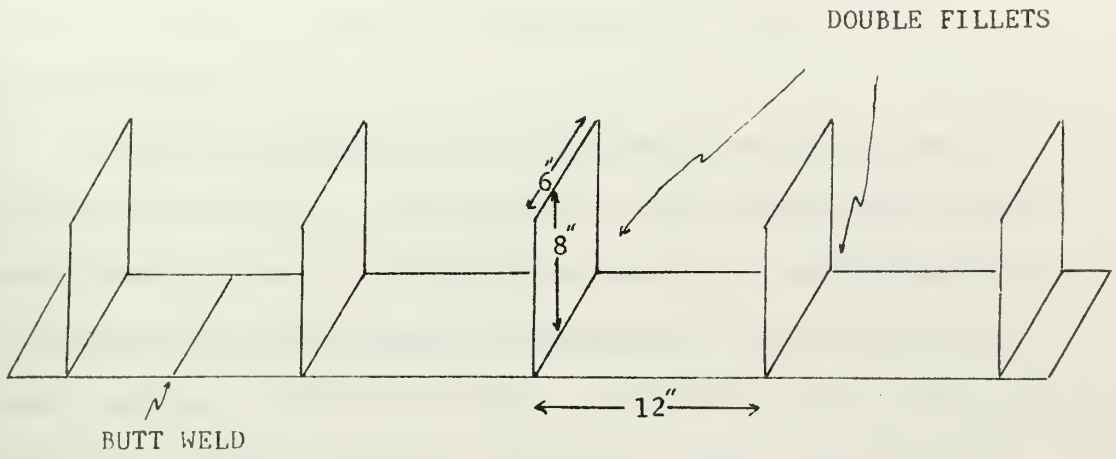

DOUBLE FILLETS
6"
8"
12"
BUTT WELD

FIG. 10

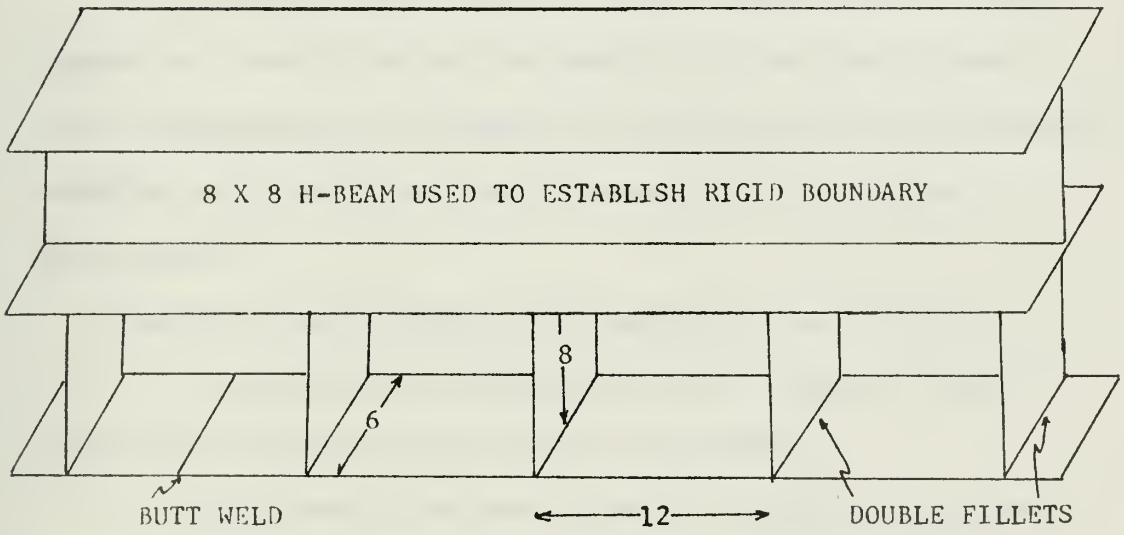

8 X 8 H-BEAM USED TO ESTABLISH RIGID BOUNDARY
8
6
BUTT WELD
12
DOUBLE FILLETS

FIG. 11

3. There is no significant change in angular distortion at the fillet welds in rigid-end structures as a result of flame straightening.

A second investigation was conducted at Battelle Memorial Institute in 1969 (7). The purpose of this research was to study the effect of flame straightening and mechanical straightening on the properties of steel used in shipbuilding. The four types of steel used were: ASTM A-517 Grade A, ASTM A-537, ASTM A-441, and ABS-B having yield strengths of 110,000, 52,000, 57,000, and 40,000 psi respectively. Distortion was produced in flat plates with no edge supports either by mechanical pressing or by a single butt weld. Plate thickness was varied from 3/8 to 3/4 inch.

To straighten the plates they were fastened with one edge clamped on a back-up plate, the other edge being free to move. Flame straightening was attempted by the spot heating and quenching technique and also by the linear technique with and without a water quench.

Results of the Battelle investigation are as follows:

1. Spot heating and quenching was unsatisfactory because the plates buckled as soon as they were quenched.

2. Linear heating was more effective although much of the straightening effect was lost when the plates were quenched.

3. Distortion in welded and unwelded plates was generally removed with equal facility.

4. In general, the A-517 Grade A plate was the easiest to straighten and the ABS-B was the most difficult.

5. The notch toughness behavior of ship steels is adversely affected by the heat of flame straightening.

II PROCEDURES

A. Selection of Parameters

Because of recommendations for further study contained in the work done by Walsh, it was decided to make an attempt to determine if, in fact, there was a corridor of yield strengths for which the flame straightening procedure was effective. One disconcerting fact, however, was the observation by the investigating team at Battelle that the higher strength steels were easier to straighten. Due to this fact, it was decided to test some type of system models constructed of materials having yield strengths above and below that of HY-80. Availability of materials dictated that we would probably have to use quenched and tempered U.S. Steel T1 as a high strength sample and low-alloy high strength U.S. Steel Corten as a medium strength sample. Common AISI 1020 plate was chosen as a low strength sample.

The choice of a system model was guided by the desire to simulate an actual shipboard type situation. Since most of the problems in shipyards occur on bulkheads and on hull plating, it was felt that a panel type model with stiffeners around the panel edges would be the best answer.

The choice of plating thickness was predicated by several factors. First of all, actual plating thicknesses encountered in ship construction were considered. A second consideration was a graph which Battelle had introduced in their report which is reproduced in figure 12.

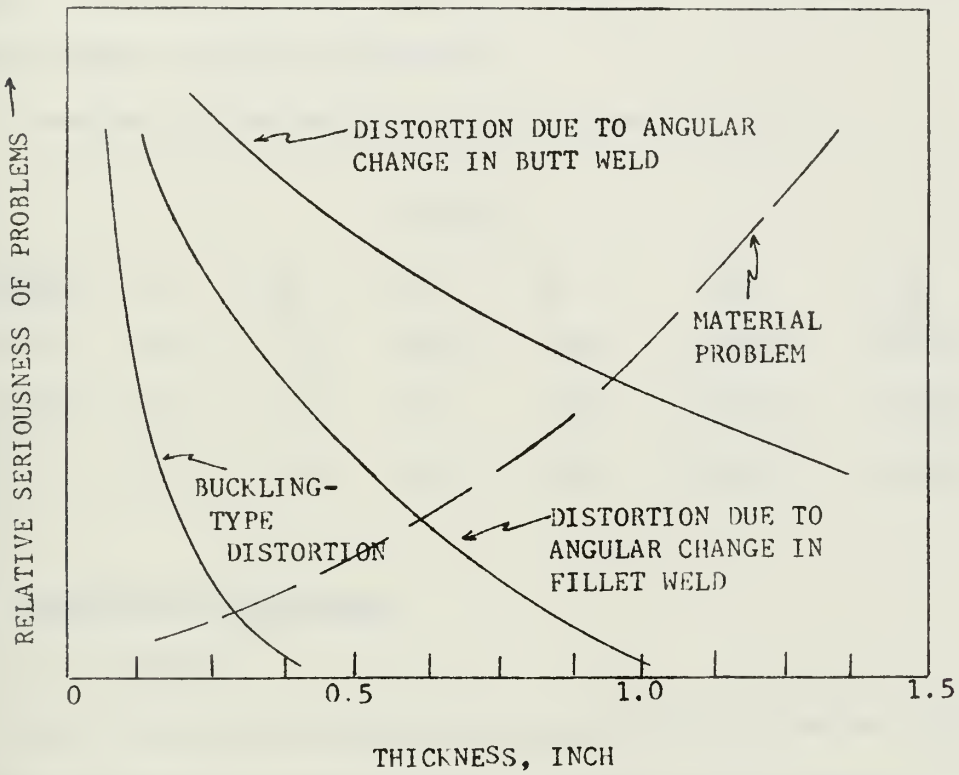


ILLUSTRATION OF THE EFFECTS OF PLATE THICKNESS ON THE RELATIVE SERIOUSNESS OF DISTORTION PROBLEMS AND MATERIAL PROBLEMS

FIG. 12

This graph, although just giving a relative picture of problems, was helpful in making a selection. A third consideration was the indication by Battelle that they had tried to construct a panel type structure of 1/2 inch plate and were unable to achieve any significant amount of angular distortion. As a result, they were not able to conduct studies on it. The final choice was that of 3/8 inch plate throughout. A diagram of the final model is shown in figure 13.

Analysis of the material used is given in table 1.

TABLE 1

MATERIAL	C	Mn	P	S	YS	TS
1020	.06	.31	.002	.024	32,000	58,000
CORTEN	.09	.36	.09	.032	51,300	72,600
T-1	.18	.90	.010	.023	118,500	134,100

B. Experimental Procedures

1. Welding

All welding was conducted by Ramsey Welding Research Corporation of Cambridge, Massachusetts. The welding was conducted using the following equipment and electrodes:

Westinghouse DC Welder

Primary Voltage:	550 volts
Primary current:	15 amps
Welding current rating:	300 amps
Voltage load:	40 volts

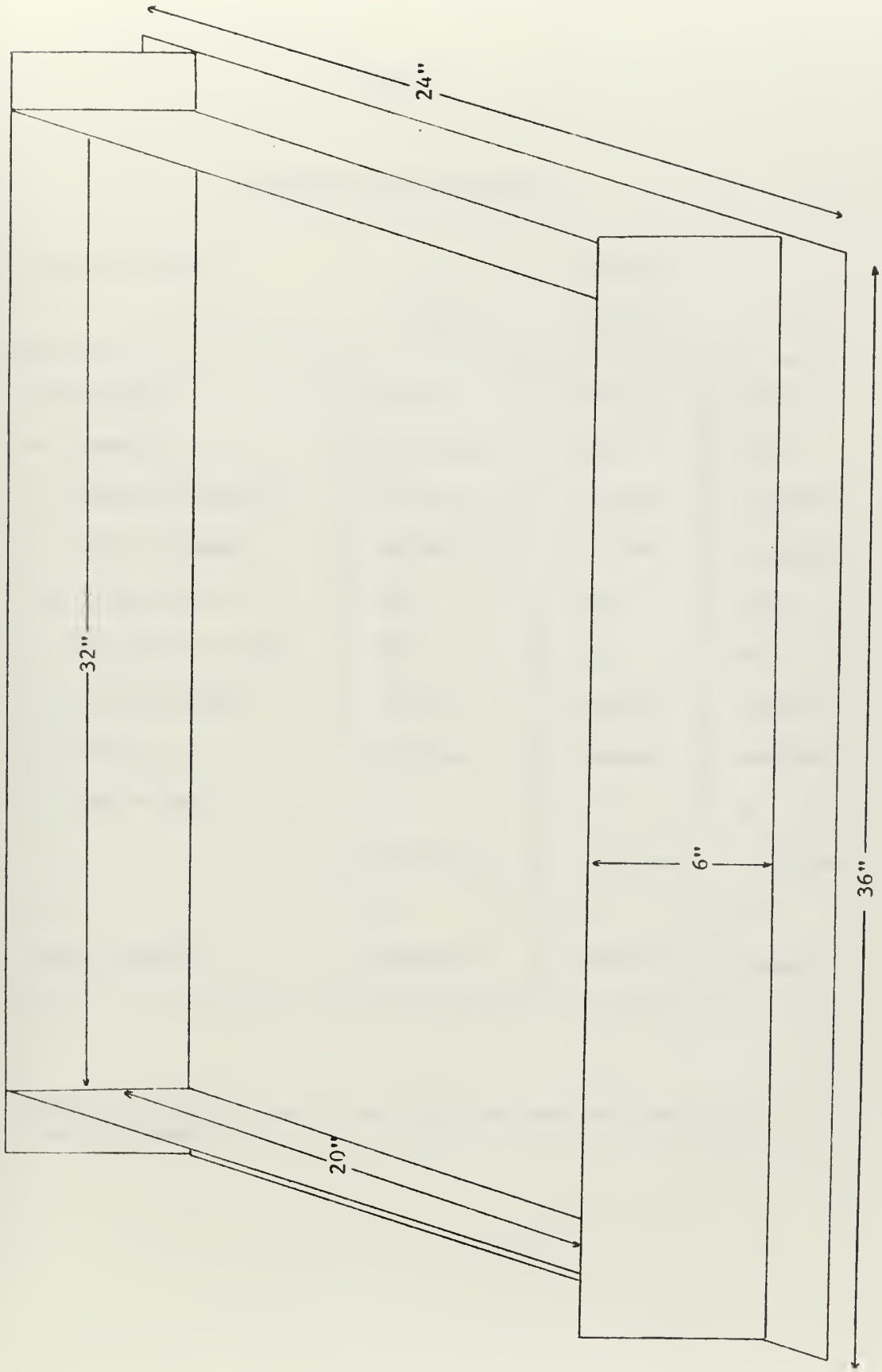


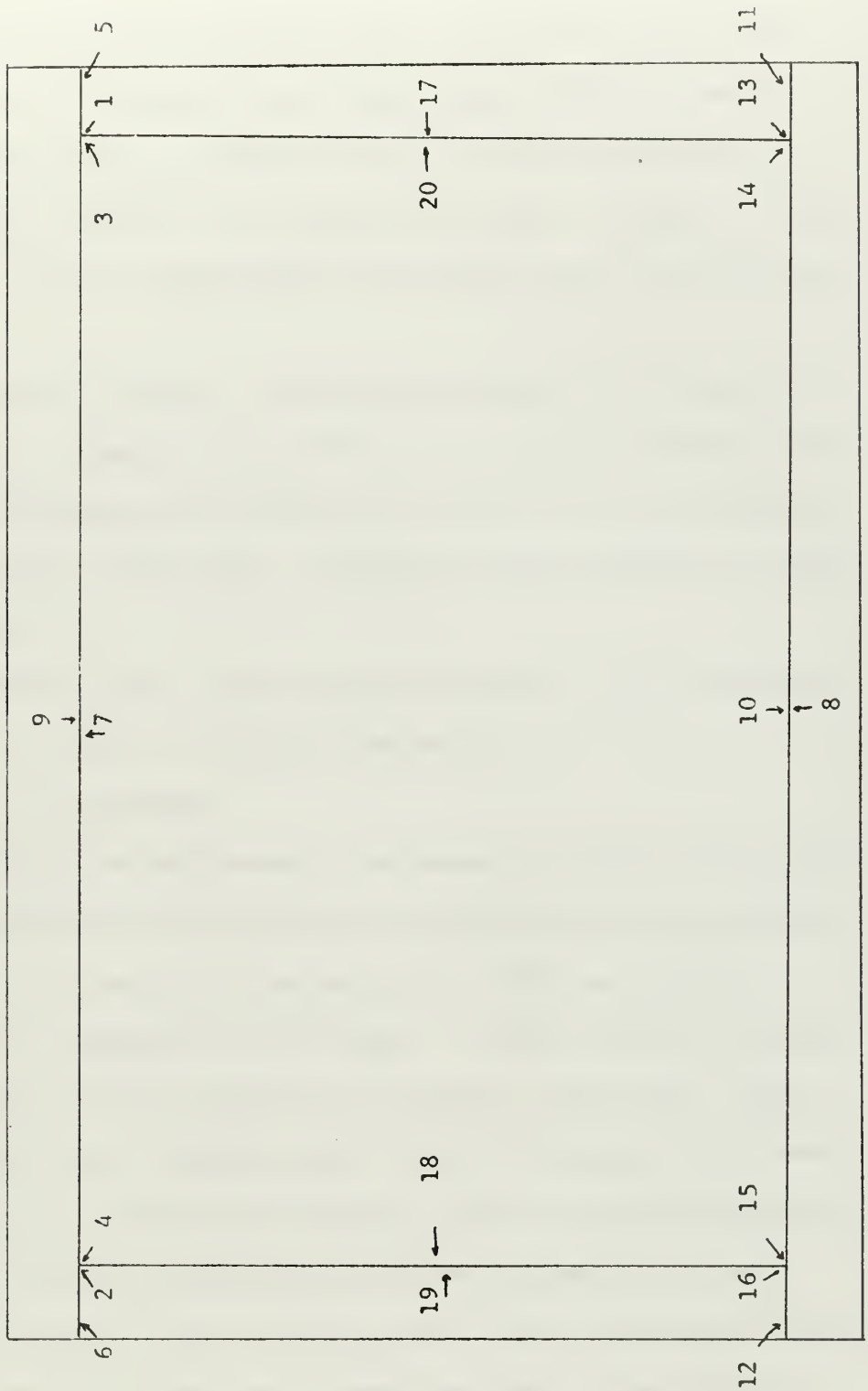
FIG. 13

TABLE 2

ELECTRODE CHARACTERISTICS

Characteristic	Model		
	1020	CORTEN	T1
1. Electrode	E7024	E10018	E10018
a. diameter	5/32-3/16*	5/32	5/32
b. tensile strength	72,000 psi	103,000	103,000
c. yield strength	60,000 psi	96,000	96,000
d. elongation - 2"	22%	24%	24%
e. reduction of area	40%	64%	64%
f. current range	160-215	120-200	120-200
h. polarity	reverse	reverse	reverse
i. type current	DC	DC	DC
2. I	160 amps	140 amps	140 amps
3. V.	20	20	20
4. Weld position	downhand	downhand	downhand

*5/32 was used on pass #1 and 3/16 was used on pass #2 on the 1020 model.



WELDING SEQUENCE

FIG. 14

Double fillet welds were used to join all of the 6 inch stiffeners to the panel and to each other. All three models were maintained in a position such that welds were made in the down-hand position. Two complete weld passes were made on each model, distortion measurements being taken after each completed pass.

Welding sequences, although not standard or optimum, were designed to insure some distortion in the panel structures. The welding sequences were maintained constant for all three models and for both weld passes. A diagram of weld sequencing is shown in figure 14.

During welding strict account was taken of all weld metal used and results are shown in section III.

2. Measurements

Distortion measurements were tkane in the following manner. After each weld pass and flame straightening pass, the weldment panels were placed on a surface plate, which was machined to within an accuracy of $\approx$ .002 inches. A dial indicator accurate to .001 inches was attached to a magnetic stand which in turn was mounted on a machined block. With the flanges of the model down against the surface plate, the dial indicator could then be used to measure deflections on the back surface of the panel. (See figure 15) Three reference points were established on each panel and every time a measurement was taken, these reference points were zeroed with respect to each other by the use of

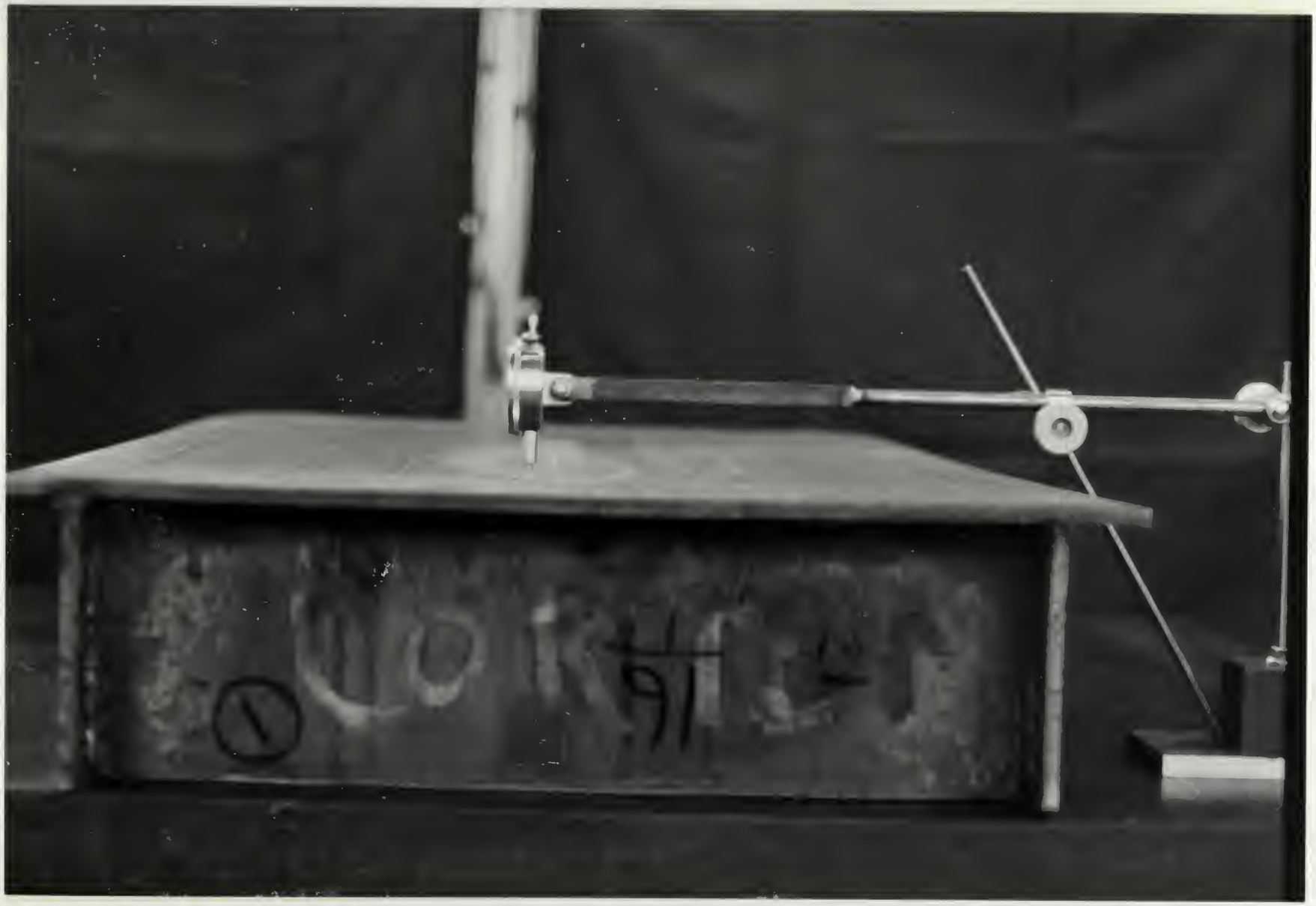


FIG. 15

shims. All distortion measurements were then in effect relative to these reference points. A grid system was established as shown in figure 16. Distortion measurements could then be taken at the intersection of each of the grid lines by moving the base of the dial indicator over the surface plate. Measurements were taken at 2 inch intervals over most of the panel with the interval being reduced to 1/2 inch in the area of the fillet welds. The reduced spacing at the welds was designed to make it easier to determine the angles at the panel edges.

When the first few sets of measurements were taken, they were repeated three times; however, the indicated deflections never changed more than ± .003 so the check was discontinued and measurements were only taken once after that.

3. Straightening techniques

Due to indications from the Battelle investigation that quenching was not effective in flame straightening and also because of a desire to eliminate as many variables as possible, it was decided to attempt the procedure without a water quench. This decision was further supported by information in the Welding Journal (8,9) that indicated the quenching procedure was not always used in shipyards.

A National Cylinder Gas Co. #3 multi-oriface oxyacetylene tip was used for all flame straightening attempts. Oxygen pressure was maintained at 30 psi and acetylene pressure was 10 psi. Surface temperature of the plate was checked with a portable

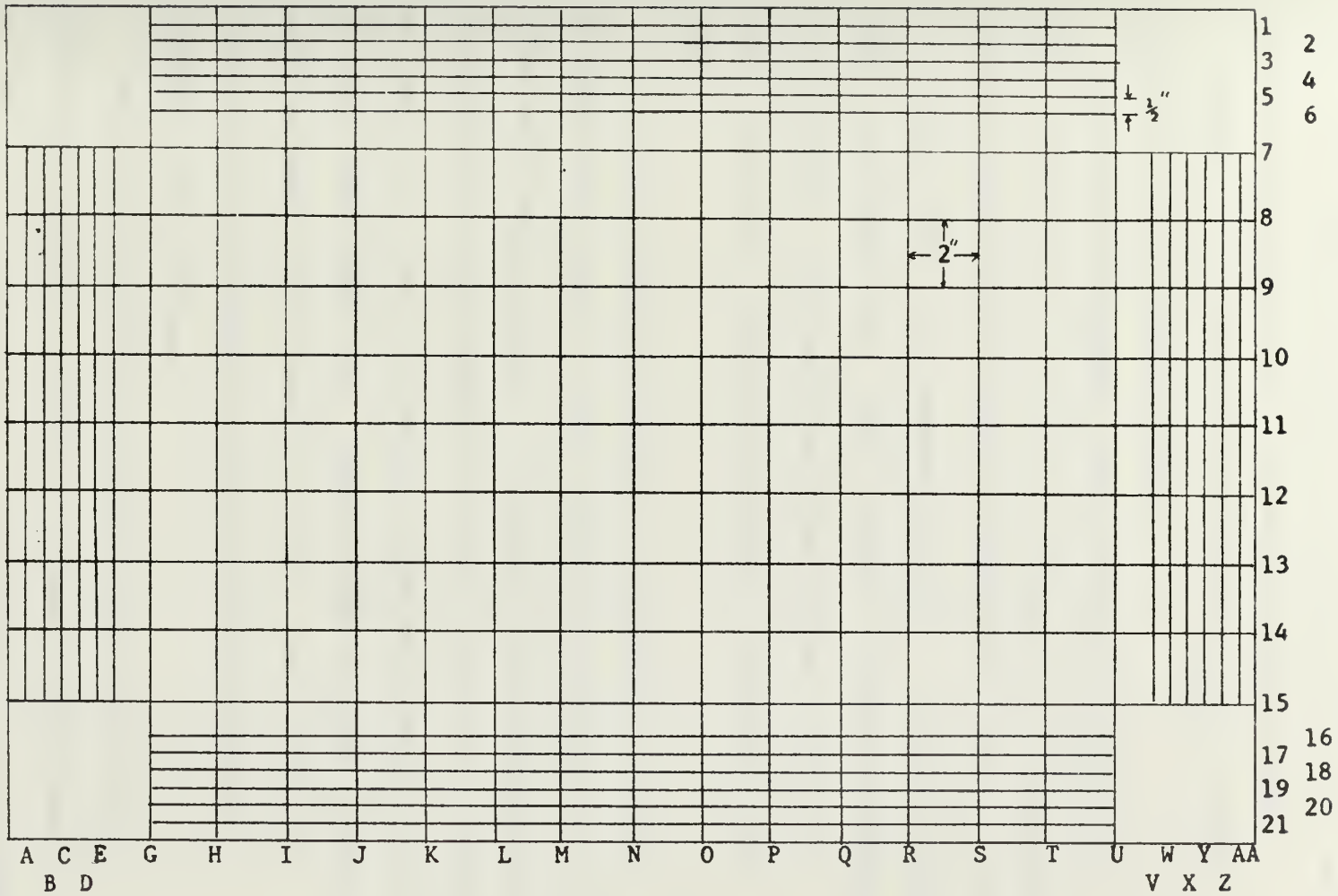

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
½"
2"
A
B
C
D
E
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
AA

FIG. 16

type chromel alumel thermocouple. The actual thermocouple was a flexible ribbon type which assured good surface contact.

Linear heating techniques were used throughout and were carried out in the following manner.

The first straightening attempt was made by heating the panel from the convex side along the mid-span of the long side. The torch was slowly moved between stations G-11 and U-11 until the required 1200° F. was reached throughout. The total heating time for each panel was: 1020--11 minutes, CORTEN--10 minutes, T-1--10 minutes. The panels were then allowed to air cool. During heating and cooling no constraints were placed on the panels.

A second straightening attempt was conducted as follows. The panels were placed on a flat surface with the backs of the fillet welds facing upwards. The torch was then applied along the back of the entire length of the weld. One side of the panel was heated at a time, with the long sides being heated first and the short sides heated last. Heating times are given in table 3. Again the panels were allowed to air cool. Due to lack of success with this technique on 1020 and CORTEN, it was not attempted on the T-1 panel.

The third straightening procedure tried was the use of a water quench technique recommended by Ramsey Welding Research. The panels were again heated in a linear manner from the concave side, a total of 3 heats being made on each panel. The first heat was between stations G-9 and U-9, the second between stations

G-13 and U-13 and the last between stations G-11 and U-11. The torch was moved slowly between the above mentioned stations until the required 1200° F. was reached throughout. After each heat, a water quench was applied with the use of a water soaked cloth. The cloth was kept saturated and the panel was quenched until the temperature was below 200° F. After the panel had been cooled in this manner, the next heat was started.

TABLE 3

HEATING TIMES 1ST ATTEMPT

PANEL	TIME
1020	11 min.
CORTEN	10 min.
T-1	10 min.

HEATING TIMES 2ND ATTEMPT

PANEL	STATIONS	TIME
1020	D-4 to X-4	13 min.
	D-18 to X-18	10 min.
	D-4 to D-18	9 min.
	D-4 to X-18	9 min.
CORTEN	D-4 to X-4	12 min.
	D-18 to X-18	11 min.
	D-4 to D-18	9 min.
	D-4 to X-18	9 min.

HEATING TIMES 3RD ATTEMPT

PANEL	STATIONS	TIME
1020	G-9 to U-9	6 min.
	G-13 to U-13	6 min.
	G-11 to U-11	5 min.
CORTEN	G-9 to U-9	5 min.
	G-13 to U-13	5 min.
	G-11 to U-11	5 min.
T-1	G-9 to U-9	6 min.
	G-13 to U-13	5 min.
	G-11 to U-11	5 min.

III RESULTS

The results of experiments on test panel are presented in the form of distortion plots and tables.

Table 4 shows the weights of weld metal used on each pass along with a figure for weight per unit length. These weights are for deposited metal and take into account the various losses encountered.

Figures 17, 18, and 19 represent the deflection measurements of the mid-span of all three panels between stations A-11 and AA-11

Figure 20 shows the normalized maximum deflections of all three panels plotted against yield strength of the material used.

Figures 21, 22, and 23 show the deflections of the mid-span between stations A-11 and AA-11 after each straightening attempt.

TABLE 4

WELD METAL USED

The figures in column 1 are total deposited metal; the figures in column 2 are oz./in. for one side only of the double fillet.

		1	2
1020			
	PASS #1	36.5 oz.	.134 oz./in.
	PASS #2	26.6 oz.	.098 oz./in.
CORTEN			
	PASS #1	43.8 oz.	.160 oz./in.
	PASS #2	43.8 oz.	.160 oz./in.
T-1			
	PASS #1	40.0 oz.	.147 oz./in.
	PASS #2	43.8 oz.	.160 oz./in.

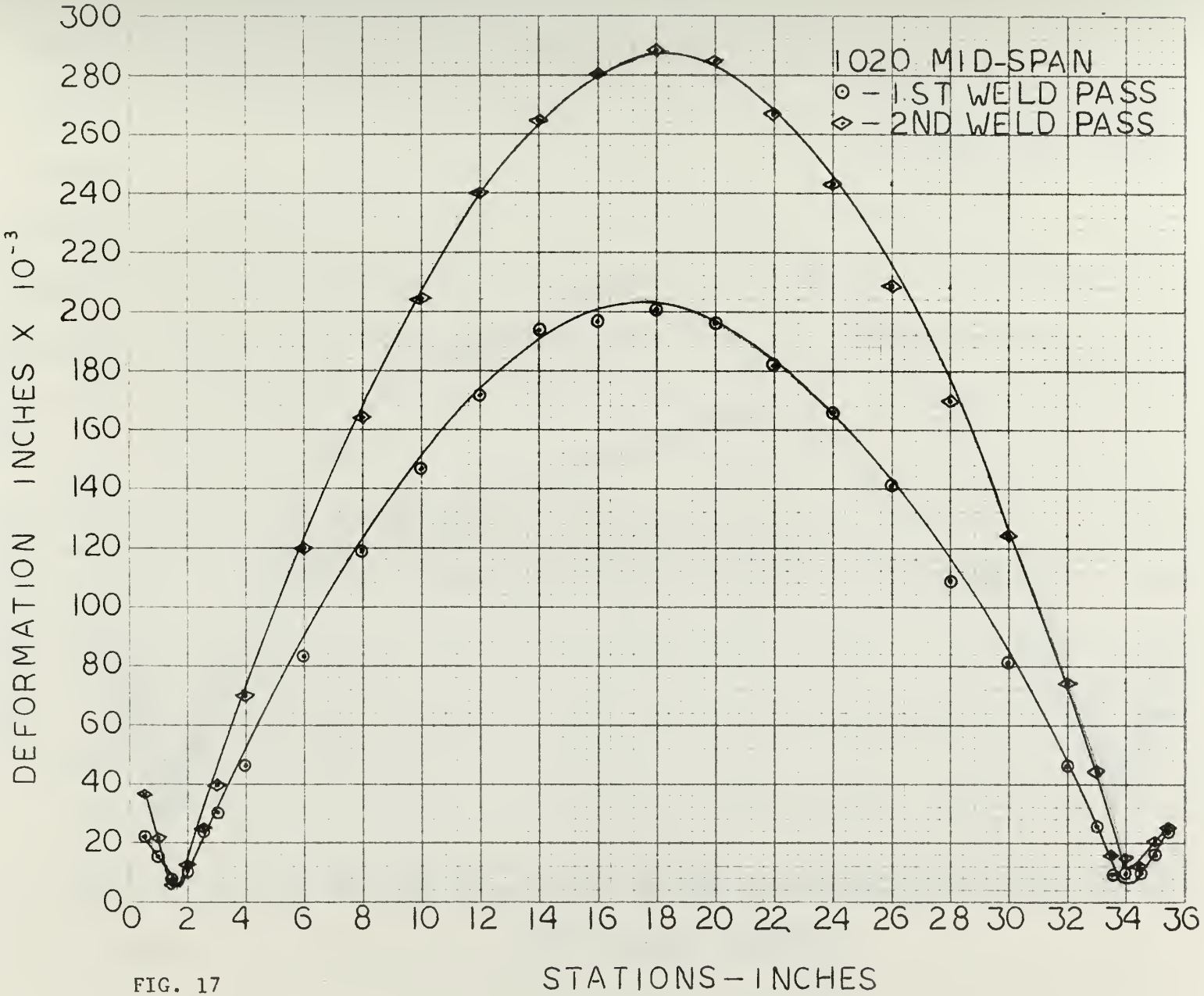

1020 MID-SPAN
⊙ - 1.ST WELD PASS
◇ - 2ND WELD PASS
DEFORMATION INCHES X 10^{-3}
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
STATIONS - INCHES

FIG. 17

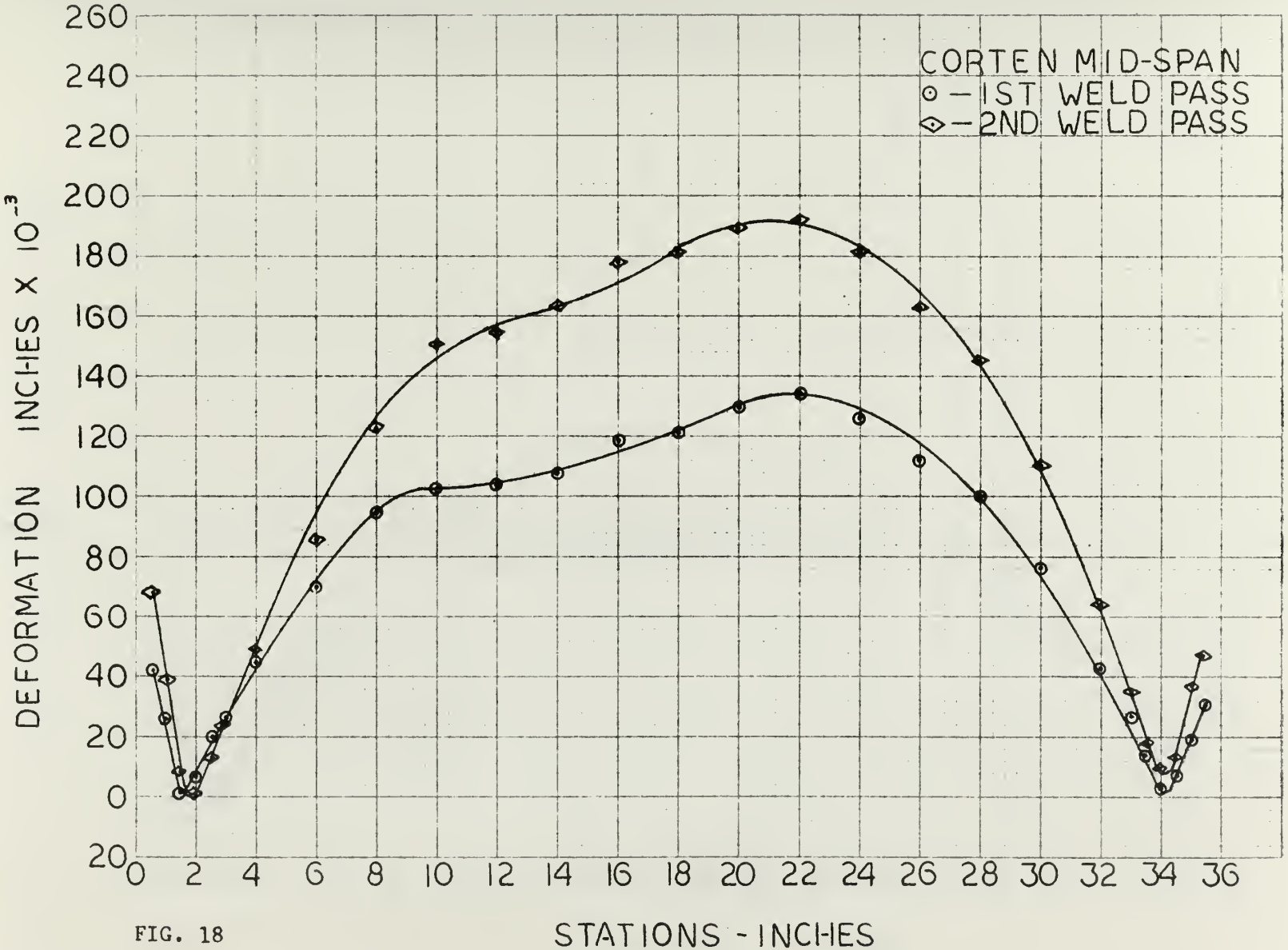

CORTEN MID-SPAN
⊙ — 1ST WELD PASS
◇ — 2ND WELD PASS
DEFORMATION INCHES X 10^-3
260
240
220
200
180
160
140
120
100
80
60
40
20
0
20
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
STATIONS - INCHES

FIG. 18

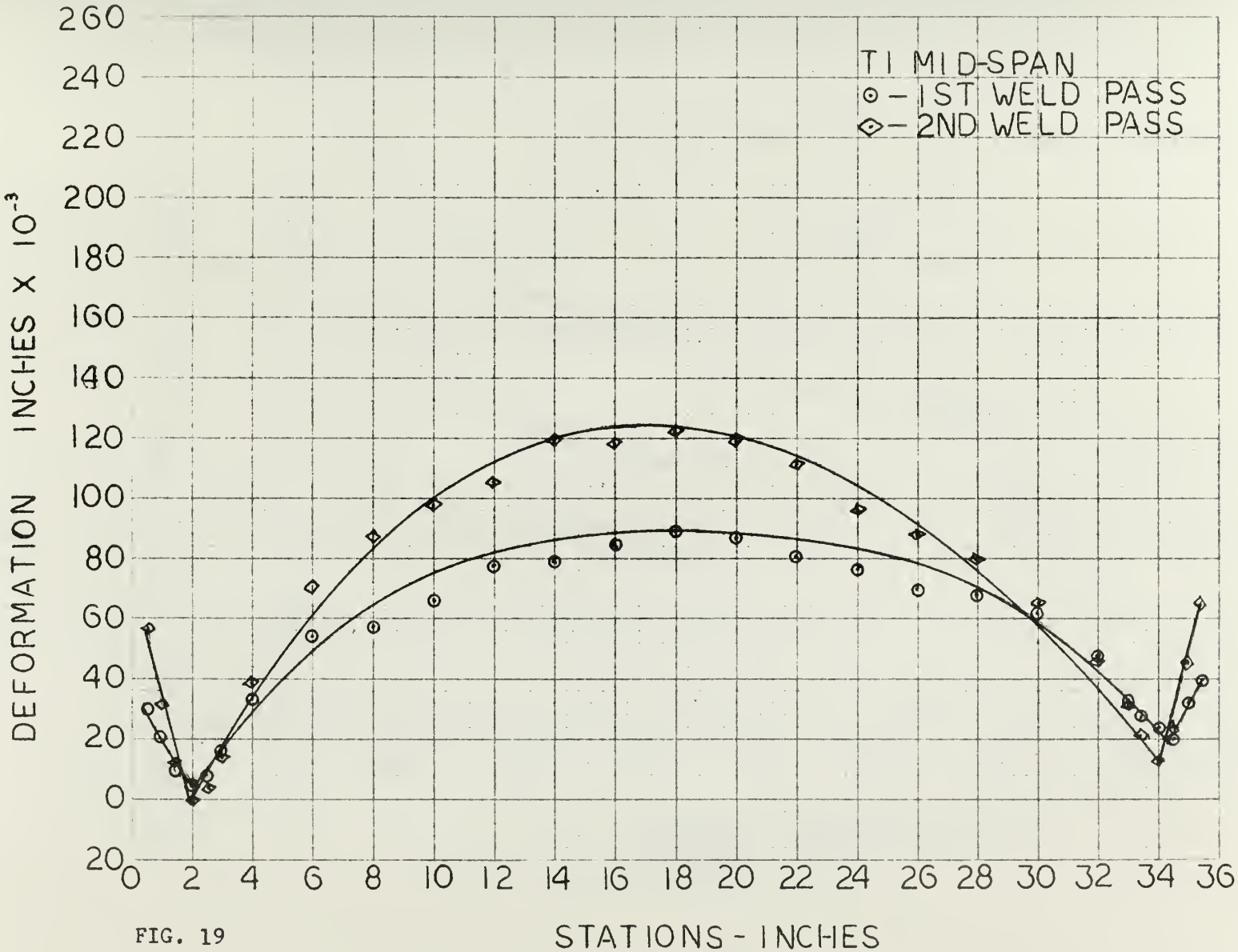

T1 MID-SPAN
⊙ – 1ST WELD PASS
◇ – 2ND WELD PASS
DEFORMATION INCHES X 10⁻³
260
240
220
200
180
160
140
120
100
80
60
40
20
0
20
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
STATIONS - INCHES

FIG. 19

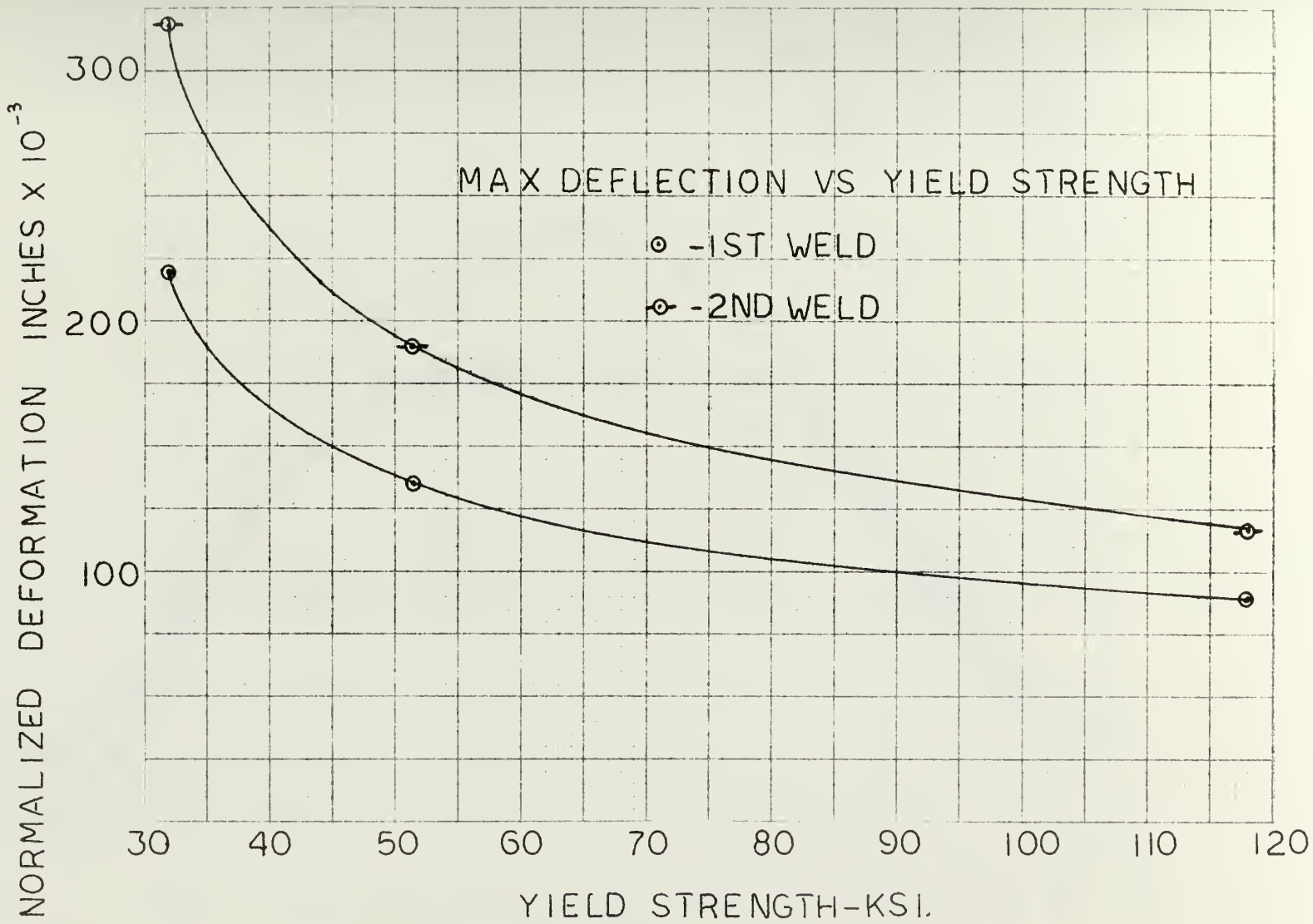

MAX DEFLECTION VS YIELD STRENGTH
-1ST WELD
-2ND WELD
NORMALIZED DEFORMATION INCHES X 10^-3
300
200
100
30
40
50
60
70
80
90
100
110
120
YIELD STRENGTH-KSI.

FIG. 20

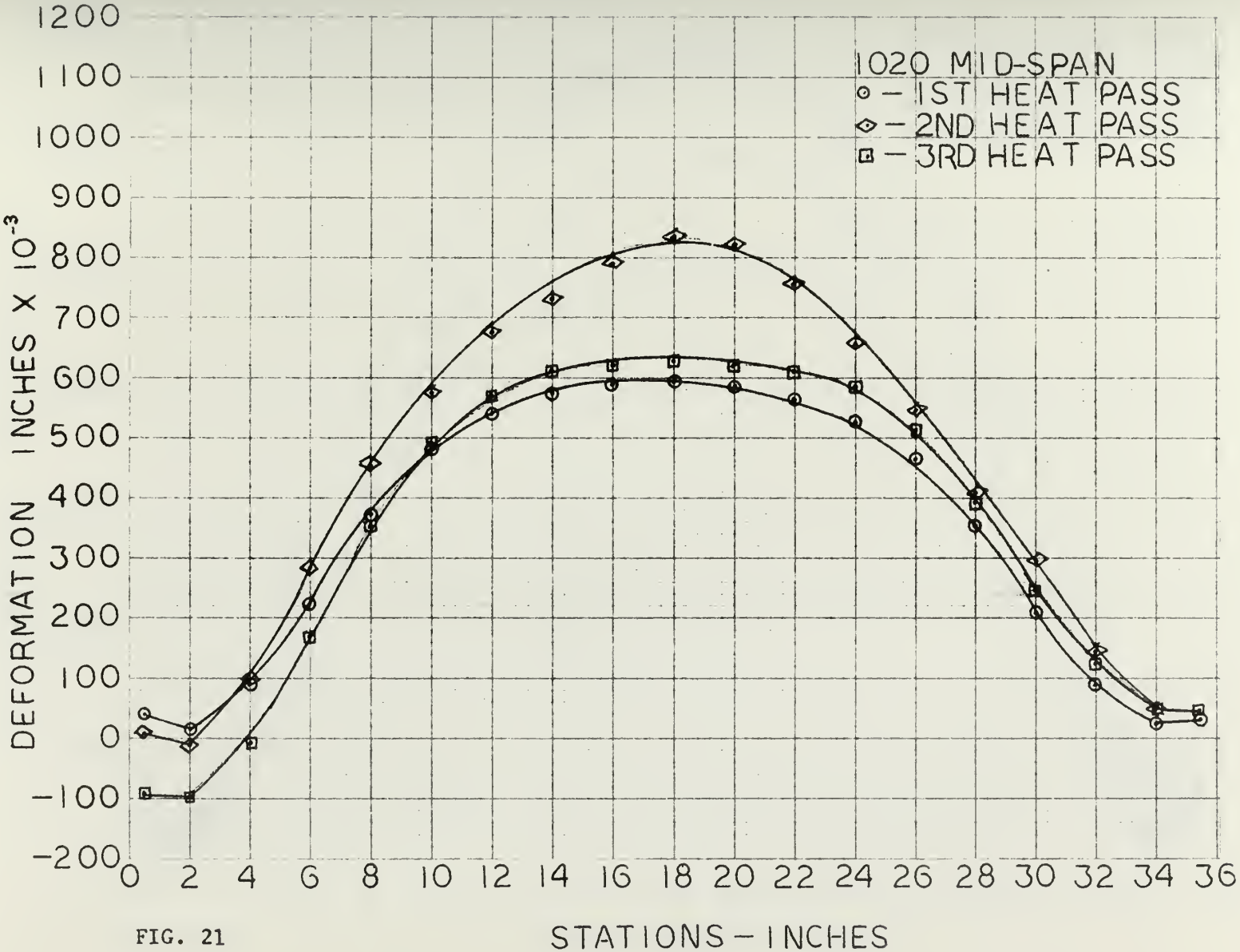

1020 MID-SPAN
⊙ – 1ST HEAT PASS
◇ – 2ND HEAT PASS
⊡ – 3RD HEAT PASS
DEFORMATION INCHES X 10^{-3}
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
−100
−200
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
STATIONS – INCHES

FIG. 21

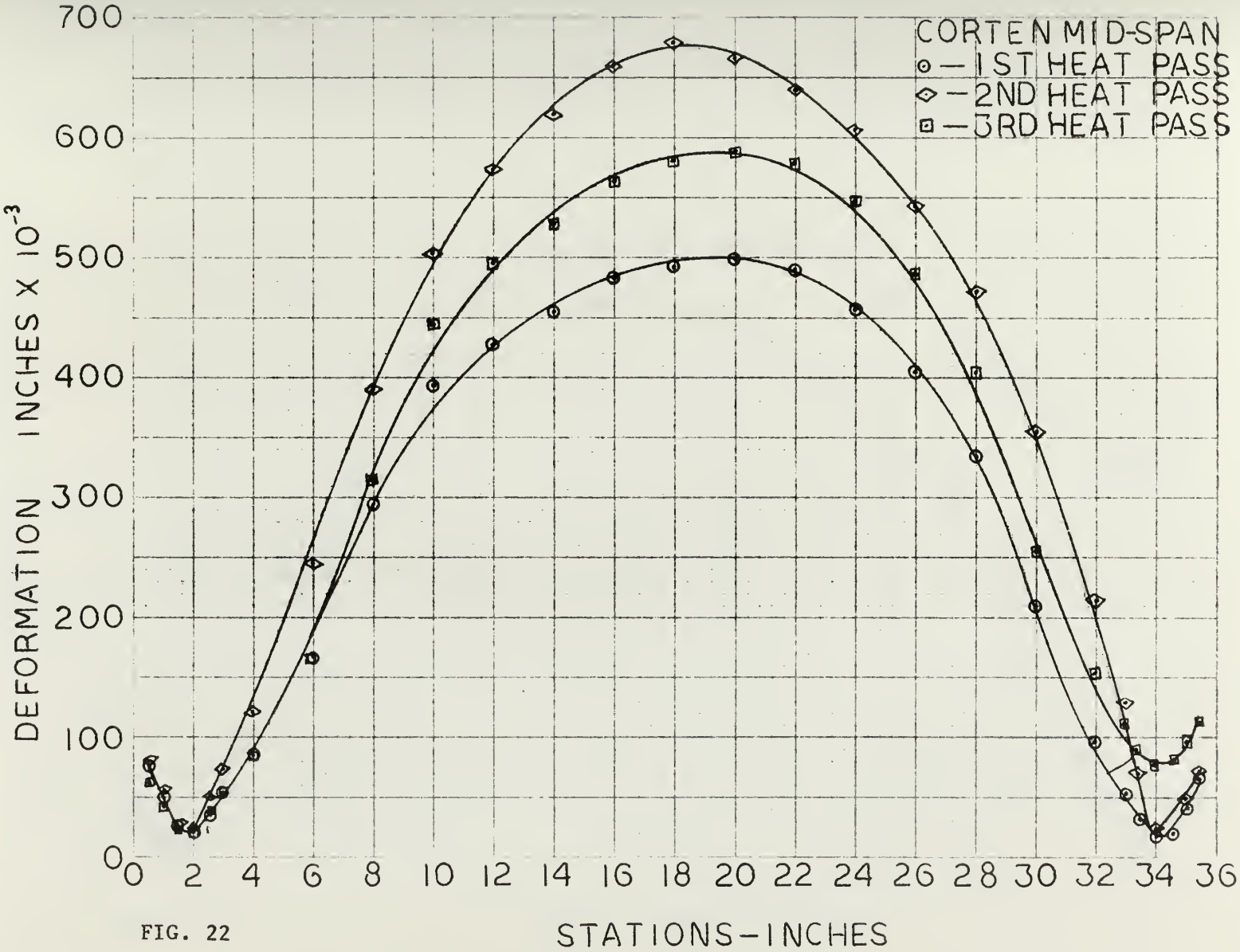

CORTEN MID-SPAN
⊙ — 1ST HEAT PASS
◇ — 2ND HEAT PASS
⊡ — 3RD HEAT PASS
DEFORMATION INCHES X 10^-3
0
100
200
300
400
500
600
700
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
STATIONS-INCHES

FIG. 22

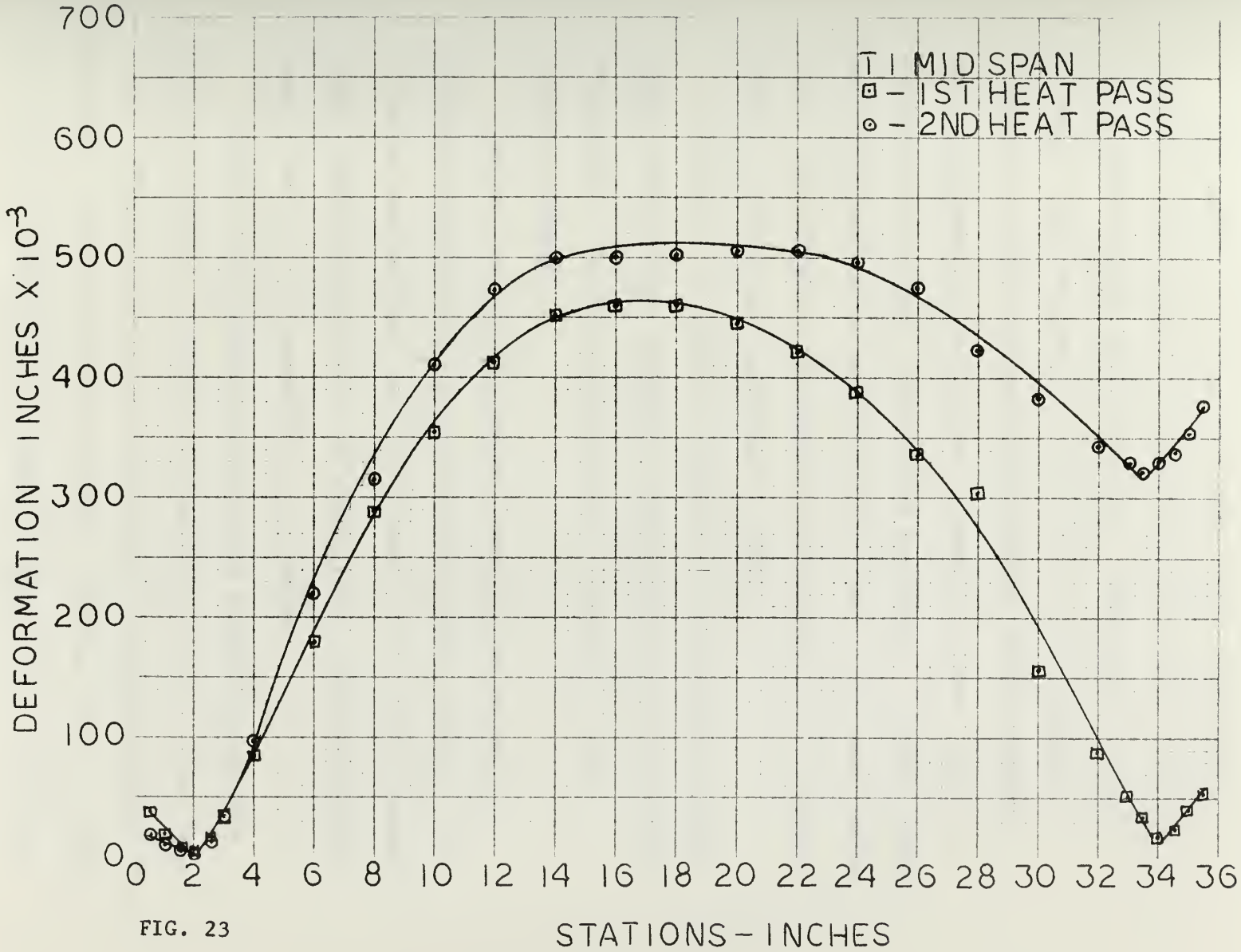

T I MID SPAN
⊡ - 1ST HEAT PASS
⊙ - 2ND HEAT PASS
DEFORMATION INCHES X 10^-3
0
100
200
300
400
500
600
700
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36
STATIONS - INCHES

FIG. 23

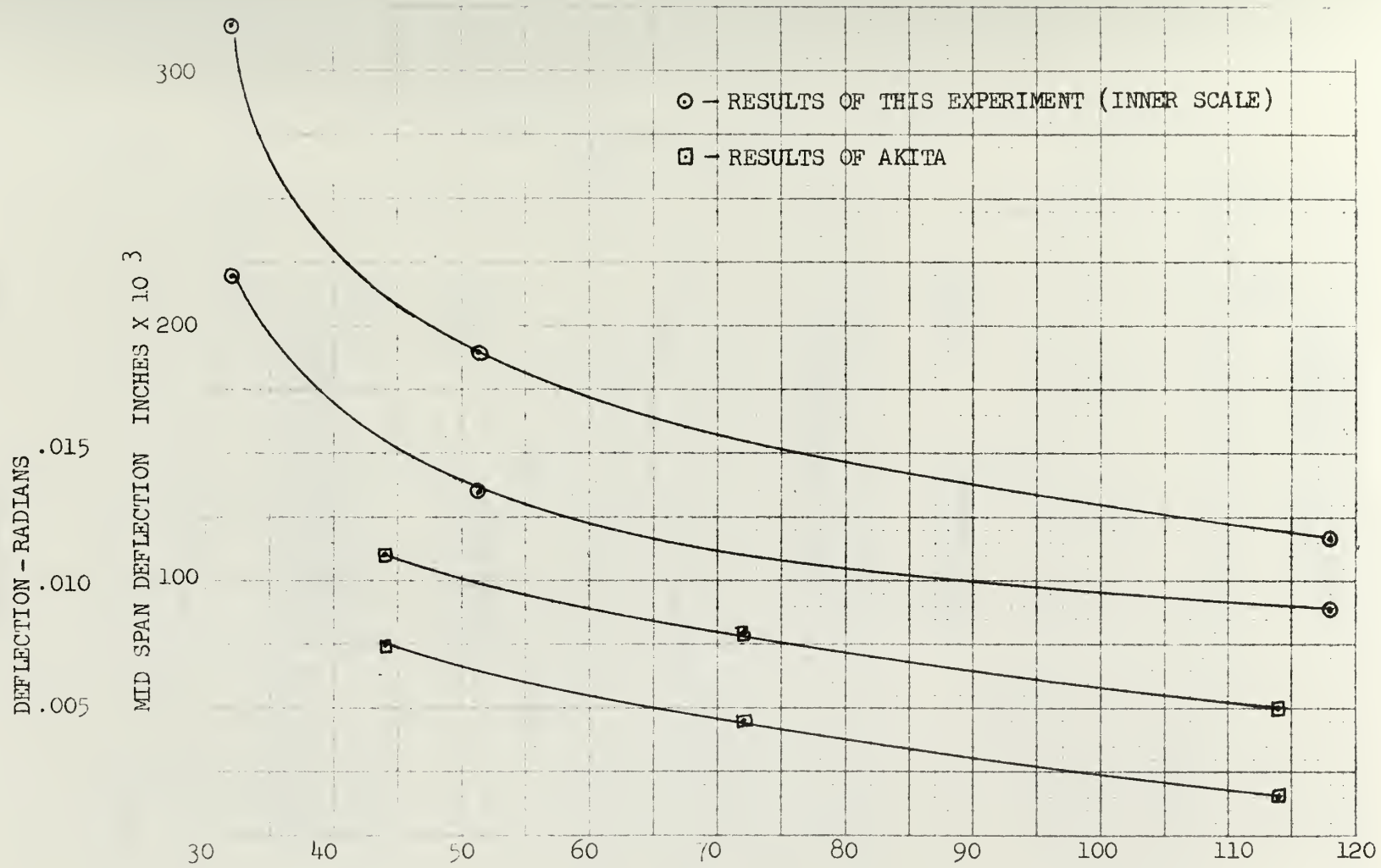
IV DISCUSSION OF RESULTS

The results of welding the panels clearly indicates a reduction in the amount of distortion for this type structure when higher strength steels are used. This appears to be in agreement with work done by Y. Akita (10). His experiments consisted of making a flame heating pass on various strength plates and measuring the angular deformation caused. This is analogous to the heat of the welding electrode. For small angles the angular deflection would be proportional to the total deflection at the mid-span. The results of this experiment and that of Akita are plotted for comparison in figure 24.

Although it is argued by Blogett (11) that higher strength steels develop higher residual stresses and thus more distortion when welded, this may be disputed for this case with the following argument.

Consider the following graphs depicting the behavior at elevated temperature of the three types of steel used (12, 13). It can be observed that the yield strength of the higher strength steels remains above that of the others while percent elongation remains lower as the temperature is increased.

Consider a two dimensional free body diagram for an area next to the weld. If we make the assumption that all welds had equal penatration, and this is reasonable since approximately the same heat inputs and weld metal deposit were used, then all welds will have the same moment arm about the neutral axis. The only



YIELD STRENGTH - KSI.
FIG. 24

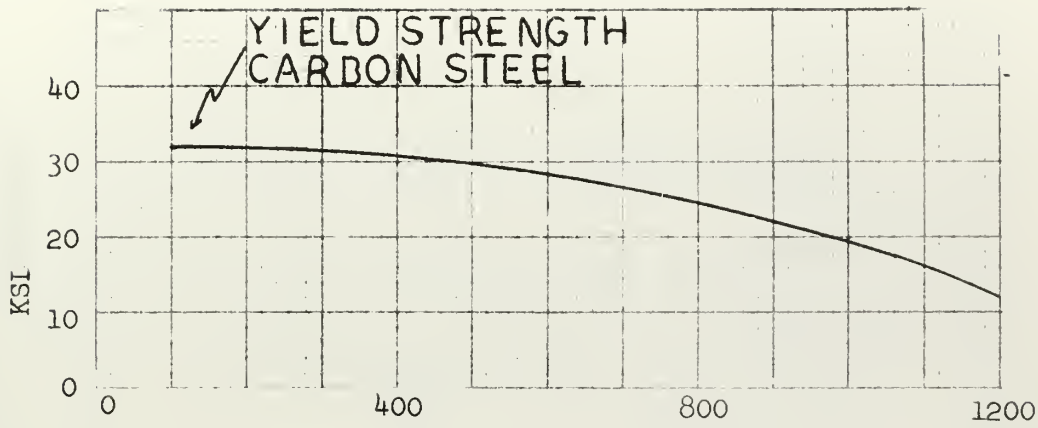


FIG. 25 TEMPERATURE -°F

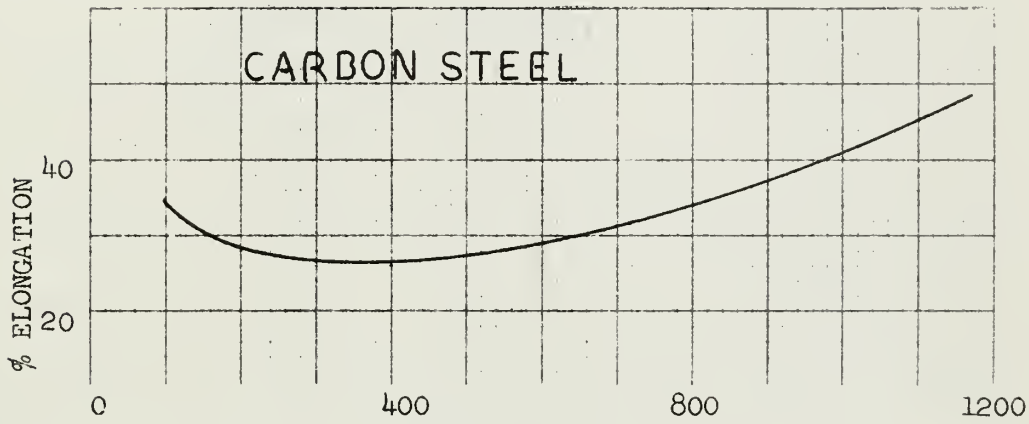


FIG. 25 TEMPERATURE -°F

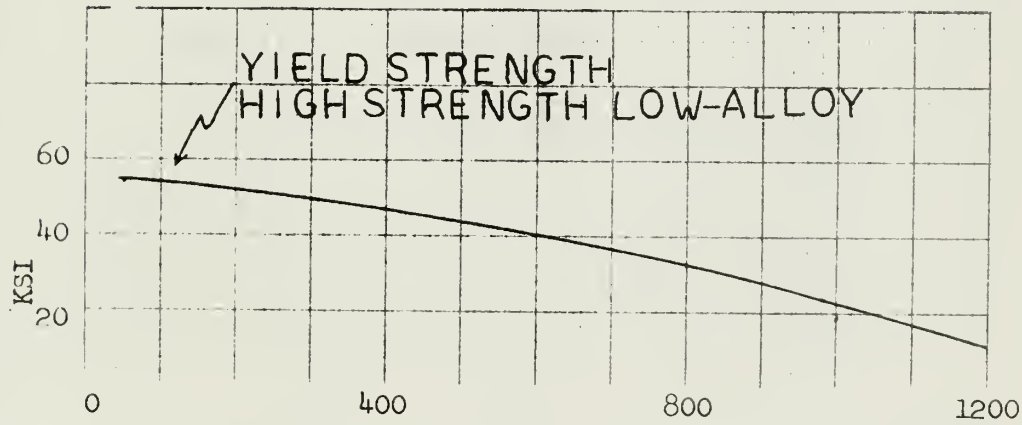


FIG. 26 TEMPERATURE -°F

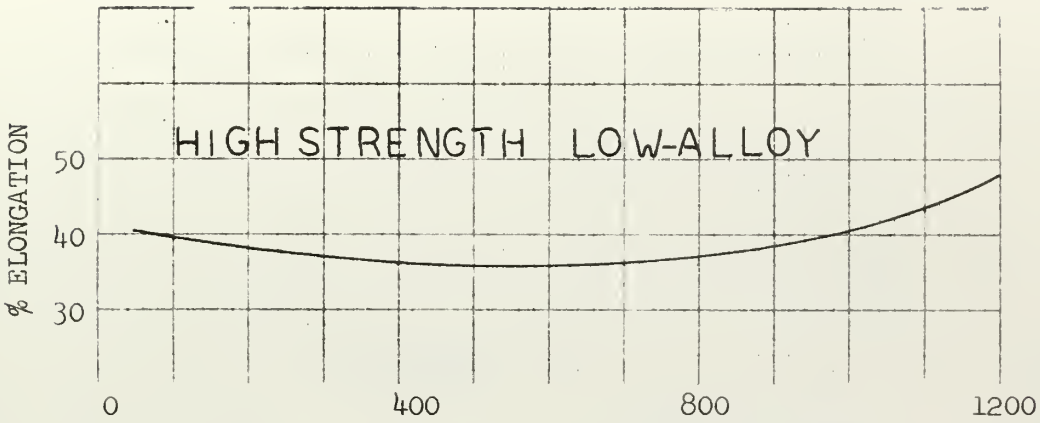


FIG. 26 TEMPERATURE - °F

FIG. 27 TEMPERATURE - °F

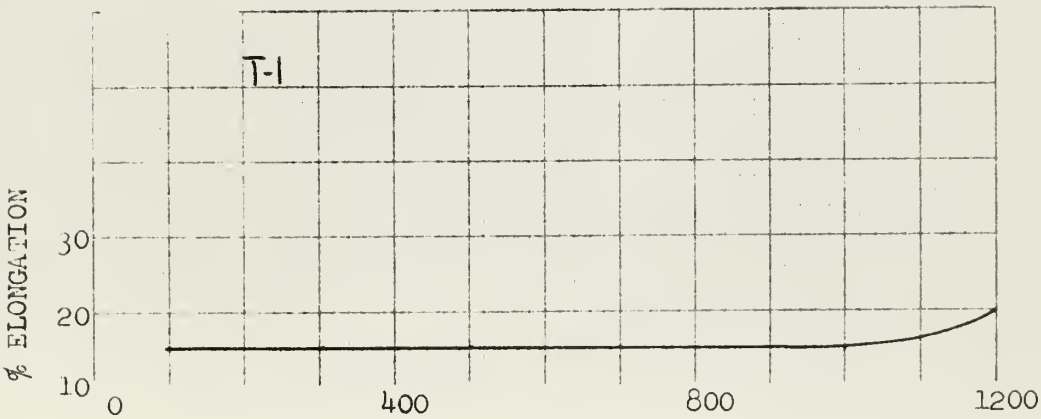


FIG. 27 TEMPERATURE - °F

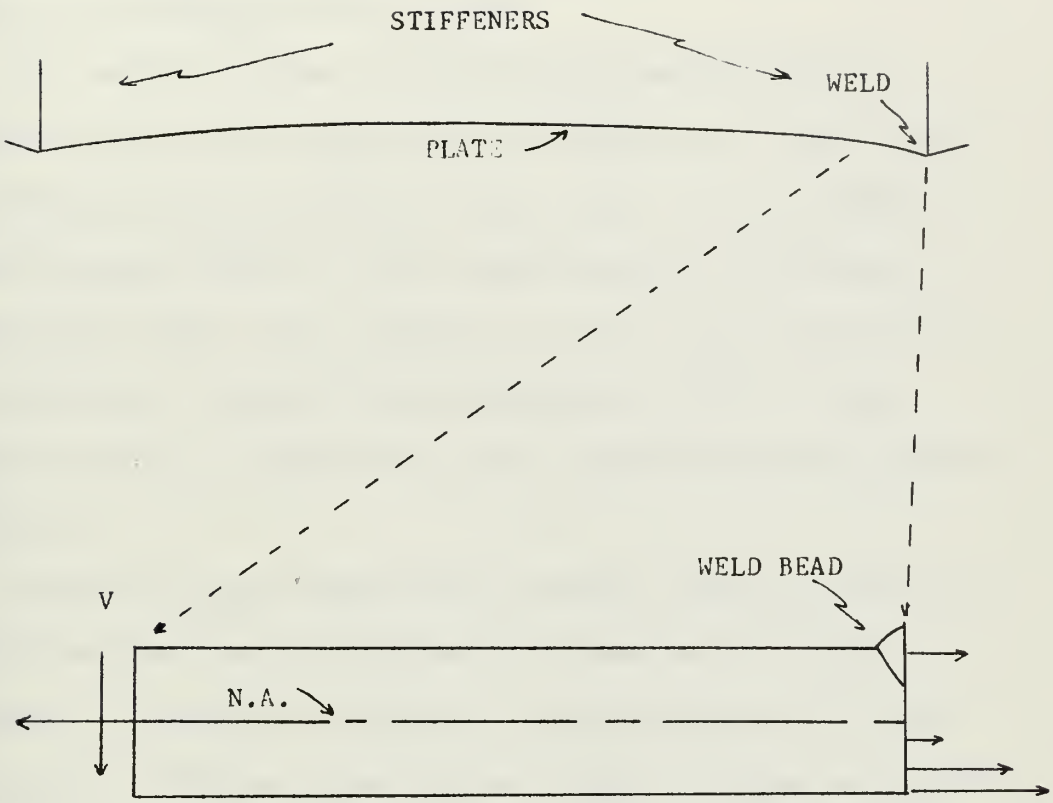


FIG. 28

forces that can then counteract this moment are shear forces V and tensile forces in the fibers below the neutral axis. In order that static equilibrium be achieved less yielding and elongation will take place in the outer fibers of the high strength steels. Thus, even though residual stresses will be higher in the outer fibers, the deformation will be less.

The results of flame straightening procedures clearly indicate that for this type of panel structure it is best to use a technique which incorporates a water quench. Both attempts which were made without a water quench resulted in increased deflections rather than a reduction. This is not to say that it is impossible to conduct flame straightening without a water quench; however, it appears that some boundary conditions make it advisable.

During the first straightening attempt, there was never any visible tendency for the deformation to move in the desired direction. Instead, the deflection only increased as the heat was applied. With the second method wherein the flame was applied behind the weld, there was visible evidence that the buckle moved in a direction so as to decrease deflection as the flame was being applied. However, no dial gage readings could be taken at this time due to the high temperature of the panel. Unfortunately, as the panel cooled, any advantage was lost as the deflection again moved in the increasing direction.

The first effect may be explained as follows. Due to the fact that there was initial deflection in the panel, any local heating will cause an increase due to thermal expansion. The effect was further magnified by the creation of a plastic hinge in the area of the flame. To further amplify, let us look at the following diagrams.

The thermal expansion below the applied heat source will cause a force P to act along the line of the plate. Due to the existing eccentricity e between the force P and the reaction R at the stiffener there will be a critical point where the force P will cause further plastic deformation of the plate.

The second instance where the panels initially tended to straighten and then went in the opposite direction is somewhat more complicated. However, one plausible explanation is that during initial heating behind the welds some of the residual stresses were relieved thus allowing the panel to return towards its original position. As heating continued further, however, a situation developed where the stresses on the heated surface were greater than on the cooler bottom surface next to the stiffener; and thus a bending moment was created which tended to increase distortion.

The only method which produced favorable results was heating and quenching. Using this technique the maximum deflection of the 1020 panel measured between the stiffeners was reduced 19% the maximum deflection of the CORTEN panel was reduced 22% and the

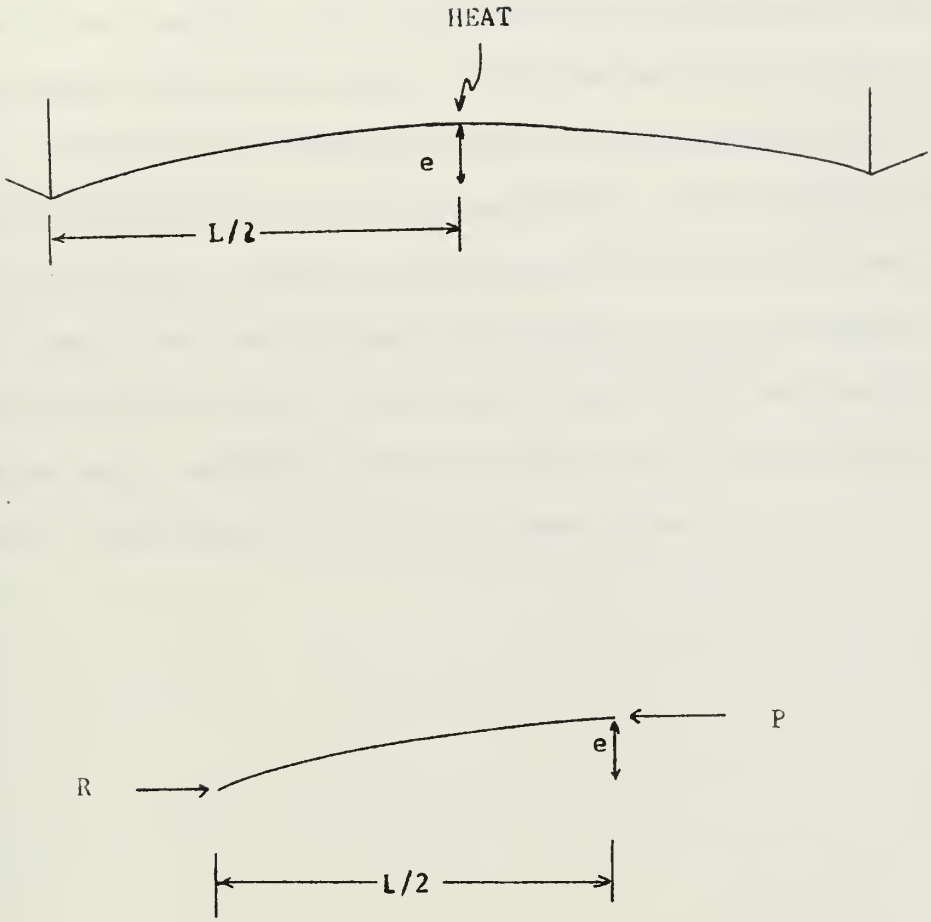


FIG. 29

maximum distortion of the T-1 panel was reduced 24%. Shrinkage stresses in the T-1 panel were such that one corner of the panel actually distorted upwards and some of the stiffeners bent thus seriously reducing the effect of straightening the mid-span. This is not to say, however, that straightening was more effective on any one panel than on any other. Quite the opposite, in fact, is true. It must be concluded that contrary to previous thoughts there is no corridor of yield strengths where flame straightening is more effective. This was an oversimplification of the problem and too many other factors must be considered such as boundary conditions, size of panel, temperature used, extent and location of heated area, quenching method whether natural air, forced air or water, and initial deflections to name a few.

V CONCLUSIONS

The conclusions of this investigation based on experimental results and the preceding discussion are:

1. Using the same welding procedures less distortion is encountered in high strength steels than in low strength steels.

2. When using flame straightening techniques on panel structures, it is necessary to use a water quench to achieve removal of distortion.

3. There is no definite corridor of steel with yield strengths where the use of flame straightening is more effective than in others.

4. Too many variables enter into the distortion removal problem to be able to make a definitive statement at the present time about flame straightening procedures that are universally effective.

5. Much further analytical, as well as experimental, work is indicated in this area.

VI RECOMMENDATIONS

It is recommended that an attempt be made to develop an analytical model for the processes taking place during flame straightening and quenching. This would, of course, have to be done for cases that are much more simplified than the one studied in this work. However, if this were successful, it would then be easier to gain a better understanding of the process in connection with more complicated structures. It should be emphasized that this is an extremely complex problem involving materials science as well as mechanics and heat transfer. A method of attack thus becomes a major question in itself, and it seems it would be a task to get interested people with the requisite backgrounds to work on.

A possible start along these lines has been made already at Battelle and at M.I.T.

The Manufacturing Engineering Laboratory of the G. C. Marshall Space Flight Center sponsered studies at Battelle under the direction of Dr. Koichi Masubuchi to develop a mathematical analysis of thermal stresses and metal movement during welding. One of the major accomplishments of the Battelle study was the development of a computer program for calculating longitudinal stresses during bead-on-plate type welding.

In May of 1969, a further study into the mathematical analysis of thermal stress and metal movement was begun at M.I.T.

The objectives of this study were the development of improved mathematical models and solutions for typical welding processes and the comparison of these theoretical results with experimental data.

The computer programs have been developed and contain a number of improvements, among which are the ability to handle butt and edge welds in addition to bead-on-plate welds.

It seems reasonable that this analysis may be extended to fillet welds and that a similar analysis could be made for flame straightening.

In the matter of the prediction of distortion, some progress has been made in conjunction with this thesis. Distortion measurements of the plates in the welded condition were used by R. Gularte of the Naval Architecture Department at M.I.T.

Gularte used the measured angles at the panel edges and input this information into the STRUDL finite element program. The plate was modeled using rectangular bending plate elements. The output deflections were within 10% of the actual measured deflections.

With this in mind, it seems that it would be possible to correlate this with experimental results on free fillet welds done in Japan. See figure 30. Using the mid-span edge angle as that being closest to the free fillet angle, it would be possible to curve fit and obtain the approximate angles all

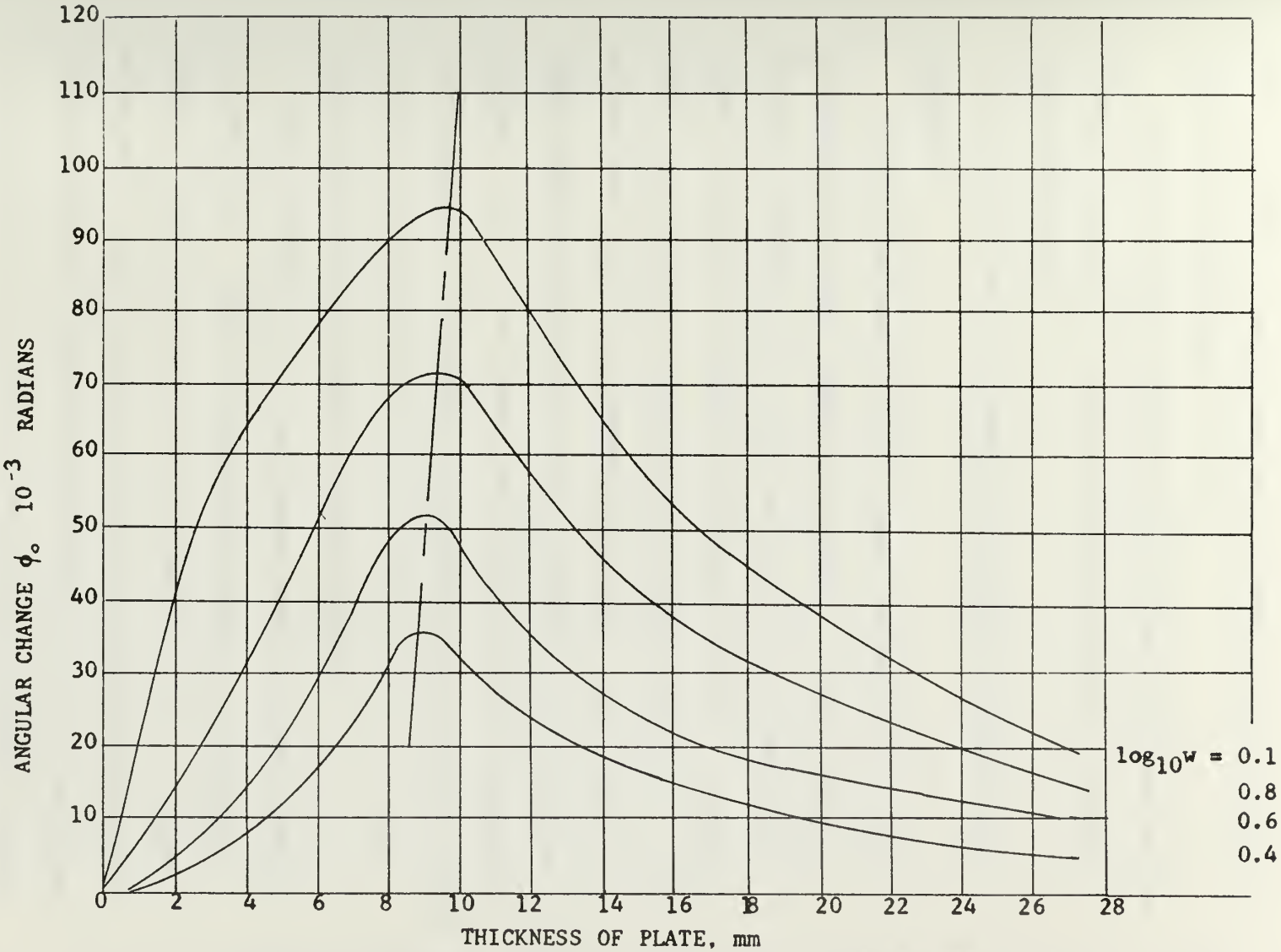


FIG. 30 Variation of angular change of free fillet welds, ϕ, as a function of plate thickness, t, and weight of electrode consumed per weld length, w.

along the edges. Again, the finite element program could be used to give deflections.

Thus, we see that knowing only the plate thickness and the weight of weld metal to be used it may be possible to predict plate deflections.

Gularte is at the present time working to develop this technique.

On the experimental level, I would recommend that tests be conducted on simple models to determine optimum conditions for flame straightening. These tests should, of course, be guided by previous practices in shipyards; however, it should not be overlooked that this process has been considered an art and has been guided by blacksmith-type ideas. For example, there remains the question of why the material must be heated red hot. Since it has already been shown that this temperature is detrimental to the material properties of high strength steels, it would seem appropriate to look at the possibility of using lower temperatures to achieve the same results.

The quenching part of the process should also be looked at more carefully. There are conflicting reports as to whether a quench is effective or if it is even needed at all. I suggest taking small plating samples which are all prebent to the same curvature, applying flame heat and varying the quench technique. The same method could be used to vary flame temperature, points of application, time span of application, etc. These results quite possibly could then be extended to more complicated systems.

APPENDIX A

NEW TECHNIQUES

Despite the many advances in welding and in the ship-building industry in recent years, it is obvious that the development of distortion control and removal techniques have not kept pace with other developments.

It has been clearly demonstrated that the use of flame straightening techniques can seriously effect the base metal properties of high yield strength steels. As a result, it is going to be necessary to develop new methods.

New methods which are being considered can be devided into basically two categories. The first one being those that involve thermal processes and the second being strictly mechanical methods.

Thermal Methods

The first of the thermal methods to be discussed is the plasma arc. The plasma arc has been developed during the past ten years as a very good tool for welding and cutting. Due to the fact that it produces a high arc temperature, it is being considered for use in thermal straightening. The advantage here being that the duration of the heating cycle could be reduced and this is known to be less harmful to base metal properties. It might even be possible to control the arc automatically in order to prevent temperature excursions into the critical range.

The development of the plasma arc for this purpose will be hindered, however, until such a time when we can make better predictions of metal responses in order to take advantage of the controllability of the plasma arc.

A second thermal method is that of induction heating. It can be said that induction heating offers the same control advantages that the plasma arc gives. However, the efficiency of induction heating is determined by the amount of energy that can be transferred to the workpiece (7). In low and medium frequency induction heating, considerable research would have to be conducted to design and fabricate coils that would transfer maximum energy to the workpiece. While it appears that fewer problems of this nature might be encountered with high frequency induction heating, this process does not appear to be suitable because only the base-plate surface would be heated due to the skin effect.

Again, as with the plasma arc, much more must be understood about metal response before it would be wise to develop this technique.

A third thermal method which comes more under the heading of distortion prevention is cryogenic liquids. The concept of using cryogenic liquids and auxiliary heat sources to control warpage and residual stresses was proposed by Harvey Aluminum (14). The concept involves altering the thermal pattern of the weldment in such a manner as to counterbalance expansion and contraction caused by welding.

The program as developed consisted of altering the thermal pattern during welding by jet spraying of liquid CO_2 with or without auxiliary heat. Combined chilling and auxiliary heating reduced residual stresses by as much as 95 percent and in some cases actually reversed normal warpage, indicating that warpage can be eliminated. Tensile tests indicated that strength was not impaired by altering the thermal patterns; in some cases it may be improved.

Many heating and chilling combinations were tested on aluminum, but the one found to be most effective was a general preheat of the plate to 200° F. with approximately 1.5 pounds of CO2 per inch of weld impinged on the seam 10 inches behind the torch.

Mechanical Methods

Two new mechanical methods of stresses relieving and distortion removal are to be considered. The first is that of vibratory stress relief.(15,16)

Vibratory stress relief is very simple in concept and involves little in the way of expensive equipment. The vibratory method introduces energy into the workpiece by means of vibrations in a low frequency range from 0 to 100 cps. In theory, this energy realigns the lattice structure to stress relieve and stabilize the part without distortion.

The equipment needed consists of a variable speed vibrator, which is clamped to the workpiece, and an electronic amplifier.

A sonic amplifier is also attached to the workpiece and transmits the vibrations to the amplifier. By varying the speed of the vibrator motor, the frequency can be varied until a resonant frequency has been reached for the workpiece. The piece is then allowed to vibrate for a period which varies in length roughly in relation to the weight of the workpiece. Usually it ranges from 10 to 30 minutes.

The Summit Fabricating Division of Hendrickson Mfg. Co. claims to be able to hold dimensional tolerances on large cranes they make to within 1/32 inch. These cranes are large enough to lift up to 175 tons and are fabricated of mild steel, CORTEN, MANTEN, T-1, or various combinations of these. Summit also used vibration to prevent weld cracking by vibrating the workpiece while welding. Since they have begun this technique, they have experienced no distortion or cracking problems.

The second mechanical method which is now in limited use is the electromagnetic hammer (17). The electromagnetic hammer, so called because it can be used in place of a hammer, consists of five essential parts: a power source, capacitors for storing energy, switches, transmission lines, and a magnetic coil. The use of electromagnetic forces to drive machinery is quite old. The direct application of electromagnetic forces for metal working is, however, a recent innovation of old principles.

The material to be deformed, or in this case, straightened, must be considered as part of the total system in magnetic forming

since its characteristics can materially change the amount of deformation for a given amount of stored energy. The conductivity of the material will determine the effectiveness of energy conversion to magnetic forces. As the conductivity of the material is decreased, energy losses take place due to heating of the workpiece. Consequently, a more conductive material such as aluminum will be deformed more at the same energy level than will a low-conductivity metal like stainless steel.

Static magnetic fields are not effective in forming metals while pulsed or transient fields are. When a heavy transient current pulse is discharged through a coil, the current creates a magnetic field causing an eddy current to flow in a workpiece in proximity to the coil. The eddy current then provides an induced field which interacts with the primary coil to create high magnetic pressure between the coil and the workpiece. If the coil is the inertially stronger, then the workpiece is formed. Unlike usual metal forming processes, most of the forming takes place after the pressure impulse has ended. The metal is rapidly accelerated, gaining a large amount of kinetic energy but moving only a short distance during the impulse. This kinetic energy subsequently does the work of forming.

This type of equipment has been used to remove the distortion from welded tanks and bulkheads in the Saturn rocket. In principle, such equipment could be useful in the shipbuilding industry, but considerable research would be needed to develop tooling for

handling high-strength steels in the thicknesses used in ship fabrication. At present, a prototype developed by NASA is being used at Avondale Shipyard, Inc. in New Orleans, La. for evaluation.

APPENDIX B

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
A7	001	016	016	003	-019
A8	014	036	037	029	-016
A9	018	044	045	034	-027
A10	025	044	050	029	-048
A11	022	037	040	004	-086
A12	019	028	033	030	-122
A13	004	015	021	017	-160
A14	-002	002	003	000	-208
A15	-005	-005	-018	-020	-245
B7	002	010	008	-006	-020
B8	010	021	020	013	-026
B9	017	030	033	015	-040
B10	019	029	034	017	-059
B11	015	022	028	-006	-096
B12	012	015	022	024	-129
B13	001	002	005	004	-165
B14	-001	-010	-011	-010	-216
B15	-003	-010	-027	-030	-247
C7	-001	-001	001	-012	-025
C8	003	007	010	-007	-040
C9	012	015	019	004	-050
C10	012	015	020	008	-074
C11	008	007	014	-009	-105
C12	008	011	010	-006	-138
C13	-005	-014	-005	-002	-178
C14	-017	-023	-022	-010	-216
C15	-008	-022	-039	-027	-253
D4	000	000	000	000	000
D5	000	002	000	-006	-001
D6	-001	003	003	-009	-006
D7	000	004	005	-008	-018
D8	009	011	013	-004	-035
D9	016	018	022	007	-054
D10	015	020	024	009	-069
D11	010	013	018	-005	-097
D12	008	005	015	-004	-127
D13	-002	-009	000	-007	-170
D14	-016	-015	-018	-016	-211
D15	-006	-020	-034	-025	-250
D16	-015	-030	-063	-059	-278
D17	-023	-037	-074	-070	-295
D18	-029	-040	-089	-091	-301

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
E4	-003	004	003	002	006
E5	003	002	002	002	001
E6	007	010	013	-009	001
E7	011	016	021	000	-001
E8	015	024	025	007	-023
E9	028	029	037	010	-032
E10	020	030	038	019	-055
E11	024	025	034	010	-082
E12	015	014	029	005	-115
E13	007	002	004	-004	-154
E14	-005	-005	-003	-005	-191
E15	-001	-013	-025	-015	-240
E16	-012	-024	-053	-042	-266
E17	-022	-033	-073	-061	-276
E18	-029	-038	-084	-085	-291
F4	-002	006	004	010	010
F5	005	005	004	017	009
F6	010	018	018	022	015
F7	017	024	028	014	010
F8	026	036	038	020	-007
F9	037	043	048	030	-018
F10	034	044	051	031	-035
F11	030	040	047	033	-060
F12	028	029	042	015	-092
F13	013	016	029	005	-133
F14	006	009	008	-001	-175
F15	004	-003	-016	-010	-220
F16	-011	-016	-043	-040	-245
F17	-017	-027	-066	-054	-264
F18	-027	-035	-080	-080	-280
G1	020	068	063	069	084
G2	015	043	039	050	058
G3	004	018	015	035	032
G4	002	011	010	013	023
G5	006	012	014	019	025
G6	013	027	030	036	033
G7	029	036	043	044	033
G8	038	054	060	055	030
G9	053	063	075	083	022
G10	027	072	089	088	020
G11	046	070	088	091	-008
G12	044	051	072	090	-047
G13	032	042	057	086	-088

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
G14	017	028	035	032	-138
G15	005	007	002	012	-195
G16	-008	-017	-012	-010	-224
G17	-016	-021	-032	-118	-241
G18	-025	-030	-045	-135	-265
G19	-019	-024	-043	-135	-260
G20	-006	-005	-023	-128	-255
G21	000	008	-010	-120	-250
H1	030	084	082	089	114
H2	023	060	056	074	091
H3	010	032	033	058	069
H4	012	026	028	029	056
H5	025	032	034	040	055
H6	015	045	049	078	064
H7	038	060	071	087	073
H8	065	090	108	122	094
H9	077	108	144	185	128
H10	086	120	196	245	152
H11	083	120	221	282	170
H12	085	103	180	271	113
H13	062	088	125	192	032
H14	040	060	080	075	-065
H15	020	028	035	077	-136
H16	005	009	010	024	-174
H17	-007	-006	-008	-087	-194
H18	-015	-016	-020	-111	-215
H19	-015	-014	-019	-110	-228
H20	-004	008	000	-104	-217
H21	000	024	014	-087	-210
I1	036	100	100	106	043
I2	030	077	074	082	115
I3	020	049	052	068	094
I4	021	044	047	067	083
I5	029	049	053	082	085
I6	038	061	072	097	091
I7	055	083	099	124	101
I8	081	119	153	198	140
I9	106	147	214	277	224
I10	115	163	300	385	304
I11	119	164	377	457	358
I12	119	149	300	380	279
I13	088	124	207	292	150
I14	051	091	133	100	-002
I15	032	048	020	064	-102

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
I16	015	025	039	031	-144
I17	001	009	022	-062	-167
I18	-004	-002	004	-091	-184
I19	-009	000	-003	-088	-187
I20	002	022	015	-085	-174
I21	005	037	030	-079	-166
J1	044	111	110	114	174
J2	038	088	087	108	150
J3	027	061	066	094	125
J4	027	057	065	094	112
J5	033	062	073	095	108
J6	046	078	093	100	110
J7	069	103	125	145	113
J8	101	168	194	243	160
J9	131	181	277	363	272
J10	146	202	380	481	420
J11	147	204	480	573	493
J12	155	188	380	540	406
J13	108	160	267	402	273
J14	077	119	177	145	062
J15	045	072	097	075	-062
J16	029	044	060	051	-108
J17	015	025	039	-045	-122
J18	000	011	020	-065	-140
J19	-002	015	020	-065	-145
J20	006	034	035	-053	-145
J21	007	051	050	-052	-131
K1	046	118	119	115	196
K2	043	096	098	105	169
K3	031	073	077	089	140
K4	034	067	075	098	130
K5	041	075	089	096	130
K6	051	091	109	130	130
K7	076	122	147	172	136
K8	119	171	227	283	188
K9	150	210	319	410	310
K10	172	235	437	548	467
K11	172	240	540	678	570
K12	159	221	441	585	492
K13	125	191	316	462	353
K14	086	143	208	177	122
K15	054	088	122	145	-028

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
K16	034	059	081	075	-079
K17	021	041	058	-010	-094
K18	000	023	034	-036	-110
K19	001	026	034	-043	-110
K20	011	043	045	-042	-099
K21	011	062	059	-040	-085
L1	054	125	121	112	220
L2	050	105	109	112	190
L3	040	080	088	112	162
L4	038	074	087	108	148
L5	047	083	100	118	142
L6	060	103	124	141	148
L7	086	136	165	207	155
L8	132	192	255	327	214
L9	164	233	353	555	335
L10	186	261	477	642	500
L11	194	265	573	731	616
L12	165	246	479	638	542
L13	143	219	349	520	395
L14	100	164	236	210	178
L15	056	103	139	160	019
L16	037	071	092	103	-037
L17	025	052	066	005	-057
L18	005	032	045	-015	-076
L19	-004	032	041	-022	-081
L20	004	050	055	-013	-078
L21	007	070	071	-015	-063
M1	063	140	142	130	237
M2	057	116	120	113	207
M3	048	090	097	099	175
M4	046	085	097	106	163
M5	053	091	109	115	162
M6	065	114	137	148	169
M7	092	147	181	205	178
M8	138	202	270	352	238
M9	177	246	371	562	355
M10	197	273	496	704	510
M11	197	281	589	790	620
M12	179	262	503	690	552
M13	142	229	370	570	423
M14	115	178	253	236	211
M15	057	113	152	145	054

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass		Straightening Pass		
	#1	#2	#1	#2	#3
M16	047	078	103	104	-010
M17	025	057	080	032	-031
M18	005	034	053	005	-054
M19	000	033	049	-007	-054
M20	007	062	063	001	-033
M21	011	082	081	030	-013
N1	071	152	155	137	250
N2	062	124	129	128	228
N3	050	094	104	112	190
N4	051	088	103	115	174
N5	056	095	110	135	168
N6	067	125	144	166	182
N7	095	157	192	219	190
N8	144	212	280	373	245
N9	182	254	383	583	355
N10	200	282	501	740	512
N11	201	288	593	833	627
N12	195	269	510	727	568
N13	150	236	378	582	450
N14	114	184	258	258	245
N15	068	121	161	132	081
N16	047	087	112	103	020
N17	020	069	088	042	003
N18	009	043	060	020	-027
N19	006	043	056	015	-026
N20	017	062	072	022	-012
N21	023	083	086	035	010
01	075	149	152	142	255
02	066	122	128	127	210
03	053	095	105	108	188
04	055	082	105	114	175
05	065	095	112	135	171
06	079	123	145	164	185
07	099	154	187	230	191
08	144	211	275	377	250
09	176	251	370	590	357
010	191	278	490	761	508
011	196	285	586	870	621
012	187	262	506	718	571
013	153	230	377	570	452
014	118	178	254	262	246
015	073	115	159	110	085

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
016	048	084	109	071	023
017	030	065	087	075	003
018	011	043	060	032	-014
019	010	042	056	015	-017
020	016	057	066	015	-001
021	027	075	082	024	018
P1	075	145	147	134	242
P2	065	119	125	134	212
P3	055	093	103	115	181
P4	054	088	101	115	169
P5	058	097	110	127	164
P6	069	113	134	150	170
P7	081	143	174	206	177
P8	129	195	251	342	232
P9	152	234	349	561	351
P10	184	261	463	590	503
P11	182	267	563	756	612
P12	175	248	484	580	562
P13	145	218	356	385	450
P14	105	170	244	258	244
P15	073	109	150	155	098
P16	054	078	106	060	033
P17	040	060	083	060	014
P18	017	042	061	026	-006
P19	013	040	056	025	-005
P20	018	056	068	019	011
P21	020	073	082	024	031
Q1	079	143	145	122	228
Q2	067	116	123	115	201
Q3	053	089	099	096	171
Q4	054	085	096	097	155
Q5	055	088	103	120	158
Q6	062	103	122	143	159
Q7	081	129	156	180	164
Q8	115	175	225	290	222
Q9	140	209	311	542	340
Q10	159	236	425	580	482
Q11	166	243	526	654	586
Q12	155	226	443	562	533
Q13	133	200	326	320	421
Q14	096	156	220	235	227
Q15	068	102	140	092	091
Q16	047	073	100	072	041

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
Q17	038	055	081	043	021
Q18	010	035	055	022	005
Q19	010	037	053	019	011
Q20	017	054	067	026	027
Q21	022	073	081	030	044
R1	075	136	139	123	202
R2	066	108	114	108	186
R3	052	082	090	099	157
R4	051	075	087	103	146
R5	055	080	092	119	140
R6	059	092	108	127	146
R7	070	110	134	159	152
R8	096	149	193	255	199
R9	115	180	264	450	312
R10	127	202	361	490	426
R11	141	209	463	545	514
R12	131	197	391	485	470
R13	109	176	285	284	375
R14	088	138	196	230	207
R15	067	093	125	082	087
R16	043	067	090	060	043
R17	035	051	073	032	030
R18	013	032	048	020	015
R19	013	034	047	023	017
R20	020	049	059	029	030
R21	027	067	076	036	047
S1	060	118	120	116	161
S2	053	091	096	105	137
S3	039	063	069	085	115
S4	037	056	064	083	110
S5	034	054	066	078	104
S6	040	071	083	095	115
S7	046	087	105	141	130
S8	067	118	153	218	175
S9	086	143	204	307	260
S10	095	162	281	400	335
S11	109	170	350	405	391
S12	098	161	306	309	363
S13	090	147	230	306	292
S14	074	117	165	210	174
S15	050	080	108	113	088
S16	040	056	078	050	048

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
S17	028	042	058	035	031
S18	009	025	039	017	014
S19	011	026	039	019	018
S20	017	039	052	024	026
S21	025	061	070	042	047
T1	045	095	098	117	127
T2	036	067	072	108	104
T3	020	037	042	080	074
T4	015	027	036	064	063
T5	015	029	035	057	063
T6	018	045	053	080	079
T7	030	060	072	093	098
T8	046	082	107	154	132
T9	058	100	139	208	177
T10	069	116	179	280	219
T11	081	125	207	299	244
T12	074	119	193	245	228
T13	072	111	162	230	204
T14	055	093	122	177	147
T15	043	065	087	095	089
T16	028	047	062	055	052
T17	021	033	047	036	038
T18	006	017	026	011	016
T19	008	019	028	014	017
T20	018	035	042	026	028
T21	030	055	062	041	045
U1	038	087	088	100	100
U2	030	061	061	070	077
U3	016	034	030	043	046
U4	015	020	023	030	040
U5	010	010	016	026	041
U6	014	025	030	043	053
U7	017	033	040	062	065
U8	022	045	057	100	089
U9	032	054	073	123	102
U10	039	069	091	155	121
U11	046	075	091	144	127
U12	042	071	097	136	111
U13	041	070	096	120	104
U14	039	061	082	108	094
U15	034	048	063	062	066
U16	022	034	048	042	032
U17	013	024	035	030	022

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
U18	001	005	014	006	011
U19	005	006	015	007	010
U20	016	024	030	021	024
U21	032	044	049	039	042
V4	011	013	016	035	025
V5	002	004	008	038	019
V6	006	013	018	040	028
V7	006	016	024	041	036
V8	008	022	031	048	046
V9	019	029	041	055	061
V10	020	043	055	104	080
V11	026	045	057	085	085
V12	026	041	060	083	070
V13	026	040	063	073	059
V14	025	039	055	056	061
V15	027	032	044	049	047
V16	018	022	034	037	037
V17	012	014	025	034	026
V18	001	004	010	011	013
W4	006	009	009	010	017
W5	005	000	002	025	010
W6	003	000	003	037	011
W7	-001	-007	002	025	010
W8	-006	-003	004	028	018
W9	002	003	016	046	037
W10	000	015	023	062	054
W11	010	016	029	055	060
W12	005	011	030	045	041
W13	007	016	030	046	039
W14	010	012	024	028	035
W15	013	006	017	029	031
W16	006	000	009	019	015
W17	005	000	009	020	014
W18	002	001	007	008	010
X4	000	000	000	000	000
X5	-005	-002	000	010	005
X6	-003	-003	000	015	003
X7	-008	-004	000	019	005
X8	-009	-003	002	023	014
X9	000	005	011	041	029
X10	001	014	023	048	045
X11	010	015	025	046	050
X12	-002	011	027	037	033

1020

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
X13	005	015	028	036	035
X14	005	011	024	029	031
X15	010	005	013	025	021
X16	006	000	008	016	015
X17	006	-002	007	009	012
X18	000	000	000	000	000
Y7	-014	-010	-007	014	001
Y8	-009	-005	002	020	004
Y9	005	003	008	037	024
Y10	008	010	018	041	039
Y11	010	012	030	040	045
Y12	-005	010	025	027	030
Y13	003	013	025	035	031
Y14	004	009	018	019	022
Y15	006	003	010	008	015
Z7	-013	-007	-005	011	-006
Z8	-005	003	006	025	008
Z9	-001	009	014	030	022
Z10	015	018	023	030	038
Z11	016	021	028	038	046
Z12	002	016	030	022	030
Z13	009	019	030	031	031
Z14	014	016	025	020	030
Z15	011	007	014	020	025
AA7	-017	-010	-008	006	-012
AA8	-002	006	007	025	012
AA9	-001	013	016	031	018
AA10	016	022	025	031	035
AA11	024	025	021	028	043
AA12	005	019	032	026	025
AA13	014	022	032	019	026
AA14	011	018	027	025	026
AA15	009	008	012	020	020

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass		Straightening Pass		
	#1	#2	#1	#2	#3
A7	014	038	042	045	024
A8	033	066	063	070	054
A9	044	070	078	077	065
A10	048	076	081	082	069
A11	042	068	077	080	062
A12	041	065	065	064	056
A13	041	062	062	063	053
A14	034	058	054	055	030
A15	021	032	027	023	006
B7	005	022	028	030	013
B8	018	040	045	048	077
B9	025	043	052	055	043
B10	027	050	054	054	047
B11	026	039	050	055	045
B12	019	034	037	040	034
B13	019	036	030	032	030
B14	016	031	027	030	015
B15	009	015	011	010	-003
C7	004	003	010	008	000
C8	010	015	021	020	015
C9	014	015	026	027	020
C10	018	022	029	030	027
C11	015	009	026	027	023
C12	010	008	014	015	015
C13	010	007	008	010	010
C14	007	004	004	005	000
C15	003	-003	-004	-003	-011
D4	000	000	000	000	000
D5	-003	-003	000	001	000
D6	-005	-004	-001	000	001
D7	-001	-002	-005	-002	-002
D8	008	006	015	016	011
D9	009	011	021	022	019
D10	015	017	028	028	026
D11	007	001	021	023	023
D12	003	002	006	005	015
D13	004	000	005	004	010
D14	005	-004	-002	-002	000
D15	000	-008	-009	-008	-013
D16	000	-007	-009	-007	-013
D17	004	-005	-005	-003	-012
D18	000	000	000	000	000

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
E4	000	000	005	004	-001
E5	004	-004	006	006	001
E6	008	001	010	010	005
E7	007	007	014	018	010
E8	016	012	024	033	018
E9	019	018	031	044	030
E10	025	023	038	047	039
E11	020	013	035	050	039
E12	012	010	020	046	031
E13	011	008	014	040	020
E14	015	006	011	031	019
E15	007	001	002	022	004
E16	007	-001	-001	003	000
E17	006	-007	-003	-001	-006
E18	-003	-005	-008	-007	-009
F4	002	001	007	006	002
F5	004	004	010	010	004
F6	011	009	019	018	015
F7	013	017	027	029	023
F8	021	022	037	040	032
F9	025	029	047	063	045
F10	029	034	053	069	055
F11	026	025	053	072	056
F12	022	023	038	069	052
F13	021	019	032	057	040
F14	022	015	025	042	031
F15	015	010	012	027	017
F16	007	003	003	014	008
F17	004	-006	000	000	003
F18	-004	-007	-010	-008	-006
G1	035	059	066	065	055
G2	031	038	044	043	037
G3	013	010	018	020	017
G4	009	002	008	007	010
G5	013	005	015	021	020
G6	018	016	027	033	032
G7	025	028	041	048	042
G8	035	038	060	080	060
G9	042	049	077	105	076
G10	045	053	087	116	086
G11	045	049	087	121	090
G12	041	046	079	119	091
G13	037	038	065	099	080
G14	030	031	048	074	061
G15	020	017	025	043	038

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
G16	007	006	014	023	024
G17	007	-005	006	016	012
G18	000	-009	005	006	010
G19	005	005	007	006	022
G20	022	039	040	038	045
G21	039	065	065	064	068
H1	042	070	073	073	074
H2	031	047	054	055	060
H3	016	023	030	031	040
H4	014	015	023	024	033
H5	018	020	030	041	039
H6	022	027	040	055	050
H7	030	041	060	083	069
H8	047	062	099	140	100
H9	058	078	131	181	129
H10	068	087	160	236	152
H11	070	086	168	245	167
H12	063	083	155	216	180
H13	054	071	124	171	157
H14	044	055	087	122	119
H15	022	028	048	059	077
H16	010	013	028	031	055
H17	002	001	016	017	038
H18	-002	-004	007	006	032
H19	004	006	014	016	041
H20	019	038	041	040	062
H21	035	062	069	065	088
I1	049	081	087	086	094
I2	046	059	064	070	077
I3	032	028	040	041	057
I4	029	023	035	037	055
I5	031	025	041	054	065
I6	041	041	058	075	083
I7	048	060	085	115	104
I8	068	088	138	202	152
I9	078	110	192	298	217
I10	091	123	250	363	268
I11	095	123	295	391	316
I12	091	120	249	341	289
I13	077	104	187	264	260
I14	062	081	129	171	184
I15	036	043	072	086	117

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
I16	018	023	042	045	087
I17	012	009	027	031	071
I18	001	-001	015	016	062
I19	002	006	017	016	065
I20	015	035	044	040	086
I21	026	057	067	064	104
J1	057	094	093	093	114
J2	045	069	075	074	099
J3	034	043	053	054	078
J4	031	033	046	045	071
J5	037	040	056	068	077
J6	046	051	074	082	096
J7	060	072	105	131	120
J8	079	106	168	245	186
J9	095	130	238	355	289
J10	100	148	318	454	370
J11	102	151	393	503	446
J12	113	148	321	462	398
J13	096	131	240	309	350
J14	074	102	164	209	237
J15	040	057	094	105	151
J16	020	032	059	059	118
J17	013	013	040	042	099
J18	-002	002	020	022	082
J19	-003	003	019	020	080
J20	007	030	039	040	099
J21	015	055	063	064	115
K1	052	093	093	092	121
K2	044	070	074	075	103
K3	032	042	052	055	083
K4	022	030	045	046	079
K5	028	034	054	072	085
K6	035	045	069	090	097
K7	043	065	101	135	116
K8	062	100	168	265	179
K9	080	125	246	381	285
K10	092	145	340	505	396
K11	104	154	428	575	495
K12	104	153	354	498	461
K13	096	137	263	350	400
K14	080	110	182	215	257
K15	045	061	105	110	166

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
K16	020	033	065	060	132
K17	004	012	040	043	110
K18	-005	003	026	025	102
K19	-010	006	023	025	100
K20	000	029	043	044	117
K21	012	055	065	066	137
L1	040	096	094	090	125
L2	088	070	073	075	111
L3	030	044	052	050	088
L4	025	033	046	045	081
L5	024	037	052	078	084
L6	030	043	071	091	096
L7	046	064	102	138	115
L8	064	099	177	266	172
L9	085	133	265	435	283
L10	090	147	363	555	407
L11	108	163	453	621	530
L12	110	164	396	525	503
L13	098	148	290	372	437
L14	191	127	214	230	304
L15	054	075	124	113	198
L16	021	035	075	065	153
L17	008	013	047	041	133
L18	-010	000	024	023	111
L19	-013	003	022	024	110
L20	-001	030	043	045	128
L21	010	055	065	067	145
M1	058	110	106	105	141
M2	055	081	084	085	121
M3	044	052	062	063	099
M4	035	041	056	055	093
M5	035	043	063	081	102
M6	045	057	084	112	119
M7	058	079	123	155	144
M8	080	117	200	309	205
M9	093	146	290	470	312
M10	104	166	399	590	437
M11	119	178	483	660	563
M12	120	177	424	575	541
M13	112	165	313	415	473
M14	101	140	230	263	325
M15	060	084	132	132	210

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
M16	028	045	082	071	169
M17	009	021	054	050	145
M18	-008	003	032	031	130
M19	-008	010	033	032	132
M20	000	031	053	050	151
M21	010	060	071	070	165
N1	058	110	106	110	141
N2	047	081	085	090	123
N3	037	049	061	062	101
N4	032	042	057	057	096
N5	035	046	066	087	100
N6	046	057	084	116	115
N7	051	082	124	167	144
N8	084	122	207	310	212
N9	098	153	300	450	325
N10	104	172	413	603	460
N11	121	181	492	680	581
N12	122	181	422	581	541
N13	108	161	308	443	460
N14	088	124	213	279	302
N15	049	075	123	139	207
N16	021	042	077	075	174
N17	010	020	053	050	155
N18	-007	007	035	035	140
N19	-012	005	032	033	137
N20	-003	030	051	052	157
N21	007	052	071	074	177
01	063	116	111	108	043
02	048	089	090	090	121
03	032	059	065	063	100
04	026	046	059	060	095
05	036	049	070	086	110
06	045	066	093	130	129
07	057	095	134	204	159
08	085	135	218	350	233
09	103	165	310	500	364
010	119	181	428	610	485
011	130	189	500	666	589
012	123	184	419	605	538
013	110	163	304	460	459
014	084	124	210	331	297
015	048	073	123	157	205
016	025	040	078	092	176

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
017	009	019	054	055	157
018	-005	004	035	037	145
019	-010	005	031	035	148
020	000	029	050	055	162
021	008	051	070	070	180
P1	064	117	109	106	132
P2	054	088	088	088	120
P3	037	060	062	062	095
P4	032	051	059	059	092
P5	037	060	072	080	103
P6	046	070	094	110	124
P7	061	098	135	175	156
P8	087	140	218	300	233
P9	108	170	307	451	360
P10	120	181	412	565	475
P11	134	192	490	640	580
P12	122	184	411	550	535
P13	105	158	296	402	450
P14	077	119	204	247	295
P15	044	068	120	112	206
P16	022	036	079	065	180
P17	009	018	055	050	162
P18	004	001	035	035	145
P19	-008	003	032	033	147
P20	000	028	051	057	165
P21	009	052	069	069	183
Q1	067	115	106	106	125
Q2	054	085	083	084	107
Q3	044	058	060	060	090
Q4	035	046	055	054	086
Q5	041	048	064	073	093
Q6	046	061	082	091	115
Q7	066	088	121	145	144
Q8	089	131	200	255	215
Q9	111	160	282	432	336
Q10	121	179	378	545	440
Q11	126	181	458	608	548
Q12	114	174	384	512	514
Q13	098	149	277	360	427
Q14	070	111	188	233	280
Q15	040	061	111	105	207
Q16	019	032	071	063	174

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
Q17	007	014	050	047	158
Q18	-006	002	034	033	147
Q19	-010	004	031	032	147
Q20	010	026	049	050	165
Q21	008	048	070	069	185
R1	067	105	095	097	110
R2	050	080	074	075	095
R3	038	052	050	051	073
R4	031	042	043	044	072
R5	038	045	050	062	076
R6	042	057	070	087	096
R7	060	079	106	127	123
R8	080	118	174	241	187
R9	098	142	249	359	293
R10	104	157	332	480	390
R11	112	163	405	542	486
R12	101	154	336	410	463
R13	088	134	248	308	389
R14	067	100	170	180	256
R15	037	054	098	100	188
R16	014	026	063	065	166
R17	004	008	044	045	151
R18	-010	-007	025	026	136
R19	-010	-003	026	025	141
R20	-001	022	046	046	157
R21	010	048	069	069	180
S1	070	104	091	000	097
S2	053	078	072	075	080
S3	043	051	048	047	065
S4	034	040	043	044	061
S5	043	047	048	057	073
S6	045	058	068	083	089
S7	059	078	097	121	117
S8	077	110	155	219	173
S9	090	129	212	322	256
S10	098	145	279	408	322
S11	100	145	336	471	404
S12	095	141	283	412	391
S13	082	123	217	301	342
S14	068	095	155	187	245
S15	040	053	095	098	189
S16	021	030	064	060	165

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
S17	013	016	046	045	150
S18	-002	002	032	030	141
S19	-002	005	033	032	145
S20	012	032	058	059	168
S21	024	059	083	075	192
T1	058	095	080	080	077
T2	043	071	057	060	061
T3	032	045	036	038	045
T4	030	035	030	031	040
T5	035	039	039	050	046
T6	037	050	052	071	065
T7	049	064	076	117	089
T8	057	088	115	195	133
T9	072	097	153	260	183
T10	074	108	189	335	221
T11	077	110	210	352	256
T12	071	110	196	315	270
T13	060	097	164	251	260
T14	054	075	125	166	210
T15	032	042	079	091	175
T16	015	022	055	051	155
T17	008	011	040	040	142
T18	-006	-004	025	027	128
T19	-003	001	031	031	135
T20	012	032	056	059	156
T21	026	063	085	084	185
U1	055	086	070	071	054
U2	040	062	046	045	037
U3	025	024	021	020	017
U4	018	020	015	014	015
U5	019	023	018	035	023
U6	022	030	031	047	035
U7	027	041	046	074	055
U8	033	054	067	125	085
U9	042	055	086	161	115
U10	044	062	099	195	138
U11	043	064	099	215	152
U12	043	066	101	201	170
U13	036	060	098	165	170
U14	035	045	080	120	160
U15	023	028	059	071	146
U16	012	015	047	003	135

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2	Straightening Pass #3
U17	006	005	036	029	127
U18	-002	-005	027	025	119
U19	-001	000	031	032	125
U20	012	030	059	060	153
U21	029	060	091	090	180
V4	013	018	003	005	007
V5	014	010	002	019	006
V6	017	016	010	027	018
V7	021	027	020	045	031
V8	020	032	027	081	051
V9	025	030	035	102	076
V10	027	032	044	119	098
V11	027	035	053	130	113
V12	026	039	065	118	129
V13	024	034	063	100	134
V14	022	026	055	075	131
V15	016	018	047	050	128
V16	009	011	041	035	127
V17	004	005	033	030	122
V18	-002	-004	027	027	116
W4	013	014	001	001	001
W5	009	006	-003	009	000
W6	011	011	000	015	009
W7	017	019	007	027	008
W8	015	016	011	040	038
W9	010	012	017	059	053
W10	011	017	023	065	079
W11	014	018	031	070	090
W12	012	023	041	068	106
W13	010	015	041	057	111
W14	009	012	035	043	113
W15	008	007	033	038	111
W16	008	008	032	033	120
W17	004	003	032	031	116
W18	-001	001	029	029	115
X4	010	010	000	000	000
X5	007	007	-005	005	-003
X6	004	006	-006	007	-002
X7	005	006	-007	011	005
X8	003	007	001	015	026
X9	003	001	005	020	043
X10	004	005	011	021	062
X11	003	010	019	023	079

CORTEN

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass		Straightening Pass		
	#1	#2	#1	#2	#3
X12	002	008	028	024	089
X13	000	005	030	025	097
X14	006	001	025	027	100
X15	003	000	026	027	106
X16	005	003	032	028	115
X17	002	002	031	027	115
X18	000	000	029	030	112
Y7	005	007	-008	010	003
Y8	003	009	004	004	025
Y9	004	009	008	009	045
Y10	007	007	014	015	060
Y11	007	013	020	019	081
Y12	007	014	028	020	086
Y13	002	011	031	020	098
Y14	008	005	028	023	099
Y15	003	001	028	025	105
Z7	009	021	006	005	012
Z8	015	026	019	018	036
Z9	016	030	027	028	061
Z10	021	036	037	041	077
Z11	019	038	042	049	098
Z12	019	040	052	053	103
Z13	013	035	055	057	116
Z14	018	028	048	048	117
Z15	011	018	045	047	120
AA7	015	035	021	020	017
AA8	020	048	040	039	050
AA9	026	060	051	055	075
AA10	032	062	062	063	100
AA11	034	067	066	070	112
AA12	031	062	072	072	120
AA13	023	058	073	073	131
AA14	028	050	069	070	133
AA15	019	034	059	060	129

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
A7	005	019	017	010
A8	010	033	023	012
A9	024	041	030	050
A10	038	056	040	070
A11	029	057	038	019
A12	030	041	031	024
A13	025	037	028	031
A14	024	030	025	042
A15	005	014	009	040
B7	-004	008	007	005
B8	002	015	011	010
B9	006	019	012	038
B10	022	030	020	050
B11	021	031	021	011
B12	015	020	017	014
B13	007	015	015	011
B14	012	017	015	022
B15	001	007	003	027
C7	-007	-004	-003	000
C8	-010	-003	-006	008
C9	-002	000	001	027
C10	008	011	009	035
C11	010	012	007	005
C12	006	003	006	001
C13	-002	000	005	-004
C14	003	002	005	012
C15	002	-002	-002	020
D4	000	000	000	000
D5	-002	-006	-004	000
D6	-007	-007	-007	001
D7	-007	-007	-005	003
D8	-013	-011	-009	010
D9	-002	-006	-003	023
D10	004	-001	004	030
D11	005	000	003	002
D12	005	-008	002	-008
D13	-010	-007	000	-010
D14	000	-005	-001	-005
D15	002	-003	-004	005
D16	000	-004	-010	003
D17	001	-001	-006	001
D18	000	000	000	000

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
E4	-001	005	001	002
E5	001	001	001	004
E6	001	002	-001	008
E7	000	001	001	010
E8	-010	-006	-002	015
E9	001	000	005	022
E10	008	003	015	035
E11	008	004	015	013
E12	007	-004	012	012
E13	-007	-002	010	008
E14	005	001	007	005
E15	008	006	006	015
E16	001	001	001	010
E17	001	-002	-003	010
E18	001	001	-001	005
F4	000	009	004	008
F5	002	009	005	010
F6	009	010	008	015
F7	013	008	012	025
F8	000	004	012	030
F9	012	013	025	030
F10	021	017	035	049
F11	016	014	035	035
F12	018	011	032	034
F13	002	013	030	025
F14	013	011	023	010
F15	016	015	018	019
F16	008	010	010	015
F17	006	005	003	015
F18	006	004	002	010
G1	024	056	052	052
G2	016	033	029	048
G3	002	010	009	041
G4	-002	004	002	041
G5	008	007	008	047
G6	014	013	016	050
G7	016	022	030	065
G8	018	025	039	065
G9	021	030	054	070
G10	031	036	076	087
G11	035	039	086	099

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
G12	029	029	075	073
G13	023	032	063	070
G14	023	030	049	037
G15	022	024	033	021
G16	015	017	022	021
G17	019	012	015	022
G18	010	012	011	012
G19	008	023	022	024
G20	015	046	042	054
G21	023	071	065	102
H1	030	067	061	124
H2	020	044	039	108
H3	005	016	016	092
H4	005	006	009	092
H5	011	010	017	097
H6	023	018	025	099
H7	021	038	047	119
H8	030	046	077	130
H9	034	053	107	143
H10	050	064	151	175
H11	054	070	180	220
H12	043	052	147	144
H13	022	052	111	127
H14	030	045	078	075
H15	019	026	042	027
H16	013	012	026	020
H17	013	009	016	025
H18	004	009	012	012
H19	008	026	027	029
H20	018	051	046	060
H21	035	078	073	098
I1	026	070	063	176
I2	015	043	034	159
I3	003	013	014	139
I4	004	006	008	120
I5	012	010	019	120
I6	022	017	029	138
I7	021	033	053	150
I8	031	051	094	151
I9	042	065	144	168
I10	062	083	214	225
I11	057	087	290	315
I12	051	071	210	216

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
I13	025	062	148	150
I14	026	044	092	081
I15	018	018	043	032
I16	005	005	020	020
I17	002	-004	008	025
I18	-003	001	006	015
I19	010	014	017	030
I20	025	042	038	065
I21	039	073	062	095
J1	033	070	060	231
J2	014	039	035	195
J3	001	012	014	184
J4	-001	007	012	164
J5	006	008	015	160
J6	017	016	028	166
J7	018	029	055	182
J8	036	060	112	176
J9	050	079	183	190
J10	065	094	269	280
J11	066	097	354	410
J12	056	081	245	266
J13	029	071	180	181
J14	028	052	111	100
J15	017	020	052	042
J16	006	003	022	025
J17	001	-002	012	022
J18	-004	-001	008	023
J19	067	013	017	040
J20	020	039	033	070
J21	032	066	057	100
K1	040	077	070	294
K2	025	049	044	264
K3	008	019	022	241
K4	004	005	012	225
K5	003	006	016	203
K6	020	012	030	201
K7	021	035	063	219
K8	048	073	136	201
K9	063	095	214	215
K10	075	105	311	327
K11	078	111	414	473
K12	064	090	310	317
K13	035	079	209	215
K14	037	059	129	120

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
K15	012	023	051	059
K16	008	007	030	031
K17	003	-001	017	030
K18	-006	001	011	021
K19	013	018	021	045
K20	025	046	040	071
K21	039	075	064	105
L1	052	086	079	353
L2	032	056	051	319
L3	017	029	030	293
L4	008	014	022	263
L5	016	015	029	246
L6	030	025	046	245
L7	031	044	077	250
L8	057	079	152	240
L9	074	102	235	221
L10	085	117	339	363
L11	079	119	451	500
L12	075	101	325	352
L13	053	089	232	230
L14	048	070	148	121
L15	020	032	066	062
L16	008	013	036	038
L17	-002	002	020	028
L18	-005	001	012	023
L19	012	018	023	048
L20	025	050	043	070
L21	041	081	070	110
M1	054	089	079	402
M2	041	062	057	372
M3	024	032	036	333
M4	017	021	030	298
M5	027	022	035	289
M6	027	032	054	290
M7	032	043	083	285
M8	059	078	153	260
M9	083	105	249	265
M10	085	118	352	379
M11	085	118	460	500
M12	081	105	339	378
M13	050	092	246	240
M14	042	062	147	138
M15	023	030	070	087
M16	010	012	038	051

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
M17	003	001	021	035
M18	-006	-001	011	033
M19	008	021	024	045
M20	025	052	046	090
M21	042	082	070	100
N1	052	091	080	444
N2	033	063	055	410
N3	017	034	032	360
N4	011	023	024	343
N5	019	025	032	338
N6	025	031	050	338
N7	033	046	082	321
N8	062	084	158	295
N9	083	108	252	295
N10	090	118	348	390
N11	089	122	461	502
N12	089	110	348	392
N13	069	092	247	251
N14	047	063	148	163
N15	020	032	071	100
N16	006	012	036	062
N17	000	001	020	056
N18	-005	-001	011	051
N19	005	016	020	055
N20	023	048	044	080
N21	040	082	069	090
O1	055	093	085	484
O2	042	067	062	452
O3	028	039	038	423
O4	018	021	027	378
O5	022	021	034	371
O6	026	030	051	370
O7	039	050	078	362
O8	062	077	147	320
O9	082	103	242	320
O10	092	120	338	405
O11	087	119	446	505
O12	086	107	340	401
O13	058	094	248	263
O14	053	069	151	170
O15	025	032	072	100
O16	015	015	041	075

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
017	007	001	020	077
018	-001	002	010	062
019	010	020	025	064
020	025	050	045	079
021	037	080	070	100
P1	063	098	085	536
P2	040	071	062	500
P3	030	044	043	464
P4	018	028	032	430
P5	025	030	041	412
P6	030	037	053	410
P7	045	051	081	391
P8	062	075	142	342
P9	081	101	226	341
P10	085	110	317	420
P11	081	111	421	505
P12	075	098	325	400
P13	052	089	231	262
P14	049	065	147	173
P15	026	033	073	100
P16	015	016	041	063
P17	010	006	027	060
P18	-003	004	015	061
P19	007	023	026	063
P20	011	047	043	078
P21	022	072	064	106
Q1	064	097	083	575
Q2	051	069	062	538
Q3	035	041	038	501
Q4	022	024	027	460
Q5	027	024	032	444
Q6	031	032	046	442
Q7	040	046	072	421
Q8	059	068	125	380
Q9	070	087	200	362
Q10	073	094	291	422
Q11	077	096	388	498
Q12	062	084	309	391
Q13	041	077	204	261
Q14	035	061	134	179
Q15	030	038	074	110
Q16	019	017	039	062

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
Q17	010	003	022	050
Q18	-005	000	011	058
Q19	007	018	021	055
Q20	013	042	037	075
Q21	023	068	059	109
R1	063	101	085	612
R2	049	073	059	572
R3	029	043	038	533
R4	024	027	026	504
R5	028	027	032	482
R6	035	033	045	480
R7	043	050	071	462
R8	059	066	115	420
R9	062	079	172	382
R10	069	079	255	425
R11	070	088	336	477
R12	056	072	260	370
R13	037	070	180	258
R14	030	062	121	170
R15	023	035	065	105
R16	017	017	037	062
R17	009	003	020	040
R18	-004	-004	008	040
R19	-003	012	016	043
R20	004	030	033	070
R21	015	055	052	112
S1	069	105	092	652
S2	055	079	065	614
S3	039	050	041	572
S4	033	032	030	546
S5	035	030	033	523
S6	041	038	045	521
S7	051	054	068	505
S8	061	069	103	465
S9	058	074	141	420
S10	072	083	202	425
S11	068	080	305	423
S12	055	063	203	350
S13	039	067	151	250
S14	035	057	104	180
S15	022	028	054	099
S16	015	013	029	061

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
S17	015	003	020	040
S18	-005	-001	010	026
S19	001	009	015	030
S20	008	031	030	062
S21	016	050	048	095
T1	063	099	082	678
T2	052	074	055	635
T3	037	046	036	602
T4	032	033	025	573
T5	037	033	034	562
T6	045	040	044	558
T7	052	056	065	541
T8	056	054	086	495
T9	061	067	113	458
T10	064	072	146	420
T11	062	065	157	382
T12	053	057	142	314
T13	052	057	111	248
T14	024	047	079	180
T15	018	024	043	090
T16	017	013	024	057
T17	013	000	014	038
T18	-002	-004	005	021
T19	-001	008	012	021
T20	008	028	030	053
T21	018	048	048	080
U1	063	095	075	700
U2	052	069	050	668
U3	041	043	034	631
U4	037	032	023	608
U5	042	036	029	593
U6	042	038	036	583
U7	046	043	045	570
U8	052	054	062	505
U9	051	049	072	445
U10	050	049	087	402
U11	048	047	089	345
U12	041	038	078	289
U13	035	032	063	230
U14	019	028	047	170
U15	014	017	028	078
U16	013	003	011	055

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
U17	007	-007	002	025
U18	-004	-009	-005	019
U19	001	008	008	020
U20	010	032	029	050
U21	023	055	054	073
V4	039	038	025	623
V5	039	036	027	608
V6	042	039	030	601
V7	042	039	033	571
V8	043	042	038	504
V9	040	036	045	440
V10	041	035	050	390
V11	033	032	052	330
V12	030	023	048	275
V13	026	020	039	220
V14	022	018	031	154
V15	010	010	019	061
V16	007	001	007	033
V17	002	-004	000	015
V18	-006	-007	-005	009
W4	039	038	026	632
W5	038	035	025	613
W6	038	032	025	605
W7	037	033	025	571
W8	036	031	025	505
W9	035	027	032	441
W10	034	028	033	393
W11	027	021	036	323
W12	025	018	030	270
W13	022	012	024	214
W14	015	007	016	140
W15	005	001	008	058
W16	006	-005	-001	025
W17	002	-008	-003	010
W18	-003	-005	-002	003
X4	040	040	028	641
X5	037	038	025	624
X6	037	031	022	605
X7	032	026	018	572
X8	034	024	017	510
X9	028	021	021	458
X10	024	018	022	394
X11	024	013	019	332

T-1

DEFORMATION - INCHES X 10^{-3}

Station	Weld Pass #1	Weld Pass #2	Straightening Pass #1	Straightening Pass #2
X12	017	010	017	264
X13	017	009	015	207
X14	005	002	005	127
X15	-003	-005	-003	057
X16	000	-006	-006	021
X17	000	-005	-005	007
X18	000	000	000	000
Y7	035	034	022	583
Y8	036	035	023	520
Y9	030	028	025	465
Y10	027	018	025	405
Y11	020	024	025	339
Y12	017	019	020	267
Y13	018	015	020	203
Y14	006	003	009	120
Y15	-006	-005	-002	048
Z7	042	046	036	602
Z8	042	052	040	560
Z9	039	048	041	485
Z10	039	051	043	430
Z11	033	046	041	355
Z12	024	034	031	276
Z13	025	032	032	206
Z14	013	020	022	127
Z15	-004	006	007	045
AA7	045	061	049	620
AA8	055	075	059	585
AA9	052	071	060	502
AA10	045	070	060	450
AA11	040	065	056	379
AA12	033	053	047	291
AA13	034	048	045	216
AA14	018	035	035	130
AA15	001	015	015	042

REFERENCES

(1.) LaMotte Grover, "Distortion and Shrinkage Problems in Ships and Other Large Structures," Part I, Welding Journal, Vol. 21, No. 10, pp. 665-675.

(2.) L. F. Bledsoe, "Repair of Welded Ships," Welding Journal, Vol. 27, No. 9, (1948) pp. 690-694.

(3.) H. Kihara, M. Watanabe, K. Masubuchi, and K. Satoh, "Researches on Welding Stresses and Shrinkage Distortion in Japan," Vol. 4 of the 60th Anniversary Series of the Society of Naval Architects of Japan, Tokyo, (1959).

(4.) Richard E. Holt, "Flame Straightening Basics," Welding Engineer, Vol. 50, (1965) pp. 49-52.

(5.) Leon C. Bibber, "Dimensional Changes in Steel," Welding Journal, Vol. 27, (1948) pp. 1009-1024.

(6.) R. A. Walsh, "Investigation of Distortion Removal in Welded Structures," Thesis XIII-A, May, 1969, M.I.T.

(7.) H. E. Pattee, R. M. Evans, and R. E. Monroe, "Experimental Flame and Mechanical Straightening and its Effects on Base Metal Properties," Project SR-185, Battelle Memorial Institute, Columbus, Ohio, July, 1969.

(8.) LaMotte Grover, "Distortion and Shrinkage Problems in Ships and Other Large Structures," Part II, Welding Journal, Vol. 21, (1942) pp. 776-781.

(9.) Matt D. Offen, "Principles of Shrinking and Straightening Distorted Low Carbon Steel Used in Shipbuilding," Welding Journal, Vol. 27, (1943) pp. 14-16.

(10.) Y. Akita and T. Yada, "A Study on Thermal Distortion of High-Strength Steel," Journal of the Japan Welding Society, Vol. 33, No. 3, March, 1964, p. 313.

(11.) Omer W. Blodgett, "Types and Causes of Distortion in Welded Steel and Corrective Measures," Welding Journal, July, 1960, pp. 692-697.

(12.) Ward F. Simmons, "Behavior of Steel at Elevated Temperatures," ASTM Special Technical Publications, 151, 180, 199, (1955).

(13.) Anonymous, "Elevated Temperature Properties of Basic-Oxygen Steel," ASTM National Meeting on Steel, January 24-29, 1965, ASTM Data Series DS-40.

(14.) D. Q. Cole, "Development of Techniques for Controlling Warpage and Residual Stresses in Welded Structures," NASA CR-61235, Harvey Engineering Laboratories, July, 1968.

(15.) Anonymous, "Stress Relieve Big Weldments in Minutes With Vibration," Machinery, Vol. 74, May 3, 1968, pp. 100-103.

(16.) Anonymous, "New Twist to the Distortion Problem," Welding Engineer, April, 1968.

(17.) Anonymous, "The Electromagnetic Hammer," George C. Marshall Space Flight Center, NASA SP-5034, December, 1965.

25 AUG 71 19537

118354
Thesis
D7837 Duffy
Distortion removal
in structural weld-
ments.
23 SEP 70
25 AUG 71
DISPLAY
19537

Thesis
D7837 Duffy
Distortion removal
in structural weld-
ments.
118354

thesD7837
Distortion removal in structural weldmen
3 2768 001 89534 5
DUDLEY KNOX LIBRARY